A STUDY OF HEAT TRANSFER TO LIQUID-SOLID SUSPENSIONS FLOWING TURBULENTLY IN A HORIZONTAL PIPE

A THESIS

Presented to

the Faculty of the Division of Graduate Studies

Georgia Institute of Technology

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy in the School of Chemical Engineering

By

Charles Marlin White

July 1955

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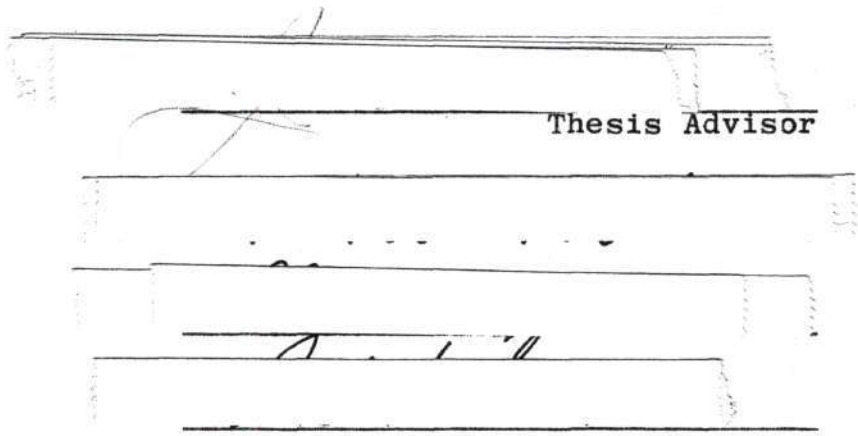

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ACKNOWLEDGMENTS

The author wishes to express his appreciation to those who gave invaluable assistance in the course of this investigation; to Dr. J. M. DallaValle, who suggested the problem and who gave indispensable advice and guidance; to Dr. Clyde Orr, Jr., whose suggestions proved most helpful in the design and operational stages of the project; to Dr. Paul Weber, who assisted in the procurement of equipment and materials; to Mr. C. A. Mayes, who helped with the construction of the apparatus; to Mr. Duane L. Franklet, who assisted in the experimental phase of the project; and to his wife, Sarah Hancock White, who assisted in every phase of the study.

The author is also grateful to the Socony-Vacuum Oil Company for making this study possible through the award of the Socony-Vacuum Fellowship in Chemical Engineering during the academic years of 1953-54 and 1954-55.

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NOMENCLATURE

a	Constant	
b	Constant	
C	Heat capacity	Btu/lb., ^{o}F.
c	Constant	
D	Inside pipe diameter	ft.
G	Mass velocity	lb./hr.,ft.^{2}
h	Average film coefficient of heat transfer	Btu/hr.,ft.^{2},^{o}F.
k	Thermal conductivity	Btu/hr.,ft.^{2}(^{o}F. per ft.)
L	Pipe length	ft.
N	k_p/k_L	
T	Temperature	^{o}F.
W	Mass flow rate	lb./hr.
x	Fraction solid material	
Nu	Nusselt number	
Pr	Prandtl number	
Re	Reynolds number	

Greek

Δ	Finite difference	
μ	Viscosity, coefficient of	lb./hr.,ft.

Subscripts

b	Sedimented bed
i	Inlet
L	Liquid
m	Mean
o	Outlet, zero fluidity
p	Constant pressure, particles
s	Suspension
v	Volume
w	Pipe wall, weight

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A STUDY OF HEAT TRANSFER TO LIQUID-SOLID SUSPENSIONS FLOWING TURBULENTLY IN A HORIZONTAL PIPE

SUMMARY

Numerous industrial processes and operations have required the heating or cooling of liquid-solid suspensions. However, only recently has the subject received any attention comparable to that accorded the heat transfer relationship for homogeneous liquids. For homogeneous fluid systems, the relationship of Sieder and Tate (1936),

$$\frac{hD}{k} = 0.027\left(\frac{DG}{\mu}\right)^{0.8}\left(\frac{C_p\mu}{k}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14},$$

has been shown to represent satisfactorily experimental data for both heating and cooling.

Bonilla, et al. (1951, 1953) studied the heat transfer to water suspensions of precipitated chalk flowing turbulently through a horizontal pipe. The maximum concentration investigated was an 18.0 weight per cent chalk suspension. In order to represent the experimental results for both water and water-chalk suspensions by a single equation, they introduced a correction factor which was directly proportional to the weight fraction of solid material in the suspension.

The subsequent investigation reported by Orr (1952) and by Orr and DallaValle (1954) was concerned with the

transfer of heat to liquid-solid suspensions flowing turbulently through a vertical pipe. Suspensions of five solid materials in water and of two in ethylene glycol were studied, and the suspension of highest concentration contained 45.7 weight per cent solid material. The experimental heat transfer results for the homogeneous liquids and for the liquid-solid suspensions were represented satisfactorily by the Sieder and Tate relationship, provided that, for the suspensions, the fluid physical properties used in the relationship were those calculated for liquid-solid systems. Separate phases of Orr's research were devoted to establishing the validity of an existing suspension thermal conductivity relationship and to developing an empirical suspension viscosity relationship for the liquid-solid systems used in the heat transfer investigation.

The present investigation was initiated in order to extend the existing heat transfer data on suspensions flowing turbulently through horizontal heated pipes. Additional information was warranted by the fact that deviations between the water and the water-chalk suspension data of Bonilla, et al. remained significant when the data were treated by the methods of Orr. Precipitated chalk, graphite, glass beads, and powdered copper were the solid materials utilized; the latter three materials were also studied in the vertical flow investigation. Essential features of Orr's experimental

apparatus were retained in order to provide a comparative study for suspensions in horizontal flow.

In the present study, water suspensions containing up to 32.5 weight per cent solid material were studied over the Reynolds number range of 11,000 to 230,000. Only the precipitated chalk suspensions presented considerable experimental difficulty. A steady deposition of chalk on the pipe wall drastically reduced the heat transfer rate toward the end of the water-chalk investigation.

Suspension physical properties were determined by the same relationships used for the suspensions in the vertical flow study. The heat capacity of a suspension was evaluated as the weighted average of the heat capacities of the components.

The thermal conductivity of a suspension was determined by using the relationship proposed by Tareef (1940) and further examined by Orr (1952),

$$k_S = k_L \left[\frac{2k_L + k_p - 2x_v(k_L - k_p)}{2k_L + k_p + x_v(k_L - k_p)} \right] .$$

This equation requires a knowledge of the suspension's volume concentration and a knowledge of the conductivities of the components.

Suspension viscosity was evaluated from the relationship proposed by Orr,

$$\mu_s = \frac{\mu_L}{\left(1 - \frac{x_v}{x_{vb}}\right)^{1.8}} ,$$

which requires, in addition to the liquid viscosity and the suspension volume concentration, the determination of the volume fraction of the solid material in a sedimented bed. By including the latter term, this expression for suspension viscosity, in a sense, considers the particulate nature of the individual solid materials. The correlation of Orr's heat transfer data obtained through use of this viscosity relationship was superior to correlations for which viscosity was obtained by other methods.

Prior to the completion of the present investigation, two other studies were reported for suspensions flowing turbulently in horizontal heated pipes. Miller (1953) obtained data for water-graphite and for kerosene-graphite suspensions containing up to 13.5 weight per cent graphite. Salamone (1954) and Salamone and Newman (1955) reported results for water suspensions of copper, carbon, silica, and chalk, with the maximum concentration studied being an 11.0 weight per cent copper suspension.

The experimental data for the homogeneous liquids and for the suspensions of higher concentration reported by Bonilla, et al., Miller, and Salamone were recalculated according to the methods of the present study. These results

have been included with those of the present study in the correlation for suspensions in horizontal pipes. The only difference observed between the correlation of Orr for vertical flow and the present correlation for horizontal flow, is that the data for the latter appear to be better represented by the Sieder and Tate equation if there is a slight reduction in the 0.8 value of the Reynolds number exponent. However, upon consideration of the differences in methods of experimentation for the four horizontal flow studies and of the limitations of the suspension viscosity relationship, another representation of the heat transfer data was not determined. For most design purposes, the Sieder and Tate relationship expresses satisfactorily heat transfer data for suspensions flowing turbulently through horizontal or vertical pipes.

CHAPTER I

INTRODUCTION

Although heat transfer to liquid-solid suspensions has been associated with numerous industrial processes and operations, it is only recently that the subject has received any noteworthy attention. Technological advances since the advent of World War II, as well as current developments in the field of nuclear reactors, undoubtedly stimulated interest for more precise information on the heat transfer properties of liquid-solid suspensions. To date, the published studies of four separate investigations have been offered to describe the heat transfer relationship for such systems.

Homogeneous liquids.--In contrast, an abundance of information has been obtained on heat transfer between solid surfaces and homogeneous liquids. As shown by McAdams (1954), for the heating or cooling of fluids flowing turbulently through pipes, a dimensional analysis of the fluid physical properties and flow factors affecting the film coefficient of heat transfer, h, has resulted in the familiar relationship,

$$\frac{hD}{k} = a\left(\frac{DG}{\mu}\right)^{b} \left(\frac{C_p\mu}{k}\right)^{c} .* \qquad (1)$$

In this equation, a, b, and c are dimensionless constants whose values can only be experimentally determined.

Dittus and Boelter (1930) correlated data for liquids of low viscosity (less than twice that of water) by evaluating all physical properties at the bulk mean liquid temperature. Their form of equation 1 results in a value of 0.8 for b and certain values for a and c that depend upon whether the liquid undergoes heating or cooling. The more logical form of equation 1 proposed by Colburn (1933) applies for liquids of higher viscosities and requires values of 0.023 for a, 0.8 for b, and 1/3 for c, regardless of whether the liquid is being heated or cooled. Viscosity is evaluated at the film temperature (the average of bulk mean liquid and average pipe wall temperatures), and all other properties are evaluated at the bulk mean liquid temperature.

Considerable data for homogeneous liquids have also been correlated by a modification of equation 1 proposed by Sieder and Tate (1936):

$$\frac{hD}{k} = 0.027\left(\frac{DG}{\mu}\right)^{0.8} \left(\frac{C_p\mu}{k}\right)^{1/3} \left(\frac{\mu}{\mu_w}\right)^{0.14} . \qquad (2)$$

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*See Nomenclature, page iv, for definition of terms in this and in succeeding equations.

The additional factor, μ/μ_w, is the ratio of the liquid viscosity at the bulk mean liquid temperature to the liquid viscosity at the temperature of the inner surface of the pipe wall. This ratio comprises what is generally the most temperature-sensitive property of the liquid at each of the two characteristic temperatures essential for heat transfer. If the liquid physical properties forming the other dimensionless groups are evaluated at the bulk mean liquid temperature, equation 2 approximates satisfactorily data for heating or cooling of homogeneous liquids at Reynolds numbers exceeding 10,000.

McAdams (1942, 1954) reports that heat transfer data for flow in tubes are correlated within an average deviation of ±20 per cent by equation 2, and that data for petroleum fractions and for water exhibited maximum deviations of +43 and -33 per cent. He also presents a more complete discussion of the Sieder and Tate equation and of the relationships proposed by earlier investigators.

Further reference will be made to equation 2 in this report, as it is the relationship by which the heat transfer results for heterogeneous systems will be examined. When the equation is used for liquid-solid suspension data, physical properties calculated for the suspension will be used in the Nusselt, Prandtl, and Reynolds groups. The viscosities forming the viscosity ratio term will be those of the suspending medium.

Liquid-solid suspensions.--Bonilla, Cervi, Colven, and Wang (1951, 1953) appear to be the first to investigate in a systematic manner those factors which should permit a determination of the heat transfer relationship for heterogeneous systems. They studied water suspensions of precipitated chalk containing up to 18 per cent chalk by weight. These suspensions flowed turbulently through a horizontally-mounted 1-1/2-inch standard I.P.S. copper pipe. The pipe had a length of 7.84 feet and was exposed to condensing steam. Thermocouples were located within the pipe wall, and thermometers were located in fluid mixing chambers at each end of the copper pipe. Trials were conducted for water and for water-chalk suspensions such that Reynolds numbers of approximately 9,000 to 300,000 were obtained.

Suspension heat capacity was calculated as the weighted average of the values for the two components. The thermal conductivity of water, rather than that of a water-chalk suspension, was employed. Suspension viscosity was evaluated by the Hatschek (1920, 1928) equation,

$$\mu_s = \frac{\mu_L}{1 - x_v^{1/3}} , \qquad (3)$$

which was derived for high concentrations (50 to 90 per cent by volume) of elastically deformable particles. This viscosity relation was chosen over other equations by the

fact that it brought the suspension heat transfer results closer to tangency with the results for water at high Reynolds numbers. All physical properties were evaluated at the mean film temperature, which was taken as the arithmetic mean of the mean wall and bulk fluid temperatures.

Employing fluid physical properties calculated by the above methods, Bonilla, et al., found the relationship

$$\left(\frac{hD}{k}\right)\left(\frac{C_p\mu}{k}\right)^{-1/3} = 0.0438\left(\frac{DG}{\mu}\right)^{0.758} - 555x_w \qquad (4)$$

to represent the experimental results satisfactorily. In this equation, x_w is the fraction by weight of chalk in the suspension. The average film coefficient of heat transfer, as determined in this investigation, was obtainable within an average error of 10 per cent by means of equation 4.

Orr (1952) and Orr and DallaValle (1954) reported heat transfer data for suspensions flowing turbulently through a vertical pipe. The following fluid systems were investigated: water; ethylene glycol; water suspensions of clay, copper, glass beads, graphite, and aluminum; and ethylene glycol suspensions of graphite and aluminum. A nominal 3/8-inch standard I.P.S. copper pipe having a heated length of 7.70 feet served as the heat exchange pipe. The temperatures along this steam-jacketed pipe were determined by thermocouples embedded in the pipe wall, and the inlet and outlet bulk fluid temperatures were measured separately by a thermocouple located within a mixing device at each end

of the copper pipe. Reynolds numbers from 3,000 to 200,000 were obtained. In addition to the wide range of physical properties afforded by the various solid materials and by the two liquids utilized, the employment of suspension concentrations up to 45.7 per cent of solid material by weight provided considerable variation of suspension physical properties.

The thermal conductivity of a liquid-solid suspension was calculated from the relationship proposed by Tareef (1940),

$$k_s = k_L\left[\frac{2k_L + k_p - 2x_v(k_L - k_p)}{2k_L + k_p + x_v(k_L - k_p)}\right] . \qquad (5)$$

Considering the equation derived by Maxwell (1891) for the electrical resistivity of a heterogeneous system containing small spheres of uniform size, Tareef reasoned that the thermal field in a two-phase system is completely analogous to the electrical field of a similar system. Equation 5 was therefore written for the thermal conductivity of a suspension, k_s, in terms of the liquid's conductivity, k_L; the solid particles' conductivity, k_p; and the volume fraction of the particles, x_v.

Using the above relationship, Tareef obtained satisfactory results for bituminous compounds with quartz sand and for aniline gum with quartz sand. Orr compared later data for bituminous compounds and sand with equation 5 and found excellent agreement.

As a separate phase of his study, Orr constructed an apparatus for determining the thermal conductivity of suspensions, and found good agreement for various concentrations of three of the systems used in the heat transfer investigation. Although Maxwell's relation was derived for systems containing low volume concentrations of spheres, the equivalent equation for thermal conductivity has been found to express satisfactorily the experimental results for suspensions of non-spherical particles at concentrations as high as 65 per cent by volume.

Viscosity measurements for the liquid-solid suspensions studied by Orr were made with a modified Saybolt viscometer. From these measurements, the empirical relationship

$$\mu_s = \frac{\mu_L}{\left(1 - \frac{x_v}{x_{vb}}\right)^{1.8}} \qquad (6)$$

was obtained. Suspension viscosity, μ_s, is related to the viscosity of the liquid, μ_L, the fraction by volume occupied by the solid in the suspension, x_v, and the fraction by volume occupied by the solid in a sedimented bed, x_{vb}. This equation represents all of the data within approximately ±15 per cent at two-tenths of the concentration of a sedimented bed, within ±30 per cent at four-tenths, and within ±85 per cent at six-tenths of the concentration due to gravity settling.

Several other viscosity relations have been proposed previously for two-phase systems. However, only one of the relationships discussed by Orr contains a term that is comparable to the x_{vb} term of equation 6. This additional factor, in a sense, considers particle size distribution, particle shape, and interfacial forces -- variables which are not considered by the viscosity relations employing only the volume fraction of solid material in the suspension. Orr attempted several correlations of heat transfer data with suspension viscosity being determined by various means, but equation 6 was found to give the best correlation.

Orr obtained satisfactory agreement of experimental heat transfer data with equation 2 by using the weighted average suspension heat capacity, the suspension thermal conductivity relationship of Tareef, and his empirical suspension viscosity relation.

Miller (1953) conducted heat transfer experiments with water, kerosene, and suspensions of graphite in these two liquids. A horizontal 1-inch standard I.P.S. copper pipe having a steam heated length of 7.96 feet was employed as the heat transfer section. Thermocouples were embedded within the wall of this pipe, and the design was such that the pipe could be rotated in order to measure the circumferential surface temperature distribution. However, only two runs were recorded for which pipe wall temperatures were measured, and the method of Wilson (1915) was used to

determine the average film coefficient of heat transfer for all other runs. Three water-graphite suspensions containing 5.85 per cent, 9.97 per cent, and 13.5 per cent graphite by weight and a kerosene-graphite suspension of 4.73 per cent concentration were investigated. Reynolds numbers in the range of 18,200 to 142,000 were obtained. Heat capacities of all materials except water were determined from measurements made with a calorimeter. Suspension thermal conductivity was considered to be that of the suspending medium. Kerosene and suspension viscosities were measured with a modified MacMichael rotational viscometer.

The results of Miller's investigation, in addition to the data of Bonilla, et al., were represented within ±15 per cent by the relationship

$$\frac{hD}{k} = 0.029\left(\frac{DG}{\mu}\right)^{0.8}\left(\frac{C_p\mu}{k}\right)^{0.4}, \qquad (7)$$

with all physical properties evaluated at the mean bulk fluid temperature.

Salamone (1954) and Salamone and Newman (1955) studied water and water suspensions of copper, carbon, silica, and chalk flowing through a horizontal, steam-jacketed, 1/2-inch standard I.P.S. brass pipe. The heat transfer pipe, which had a heated length of 8-1/2 feet, was provided with six thermocouples embedded in the pipe wall. The bulk fluid temperatures were measured by thermometers located in the

mixing chambers at each end of the brass pipe. Suspensions containing up to 11.0 per cent of solid material by weight were investigated for Reynolds numbers in the range of 14,000 to 140,000.

The data of Salamone and representative data from the studies of Orr and of Bonilla, et al., were found to be expressed satisfactorily by the equation

$$\frac{hD}{k_L} = 0.131\left(\frac{DG}{\mu}\right)^{0.62}\left(\frac{C_{pL}\mu}{k_L}\right)^{0.72}\left(\frac{k_p}{k_L}\right)^{0.05}\left(\frac{D}{D_p}\right)^{0.05}\left(\frac{C_{pp}}{C_{pL}}\right)^{0.35} \quad (8)$$

The apparent suspension viscosity was determined from pressure drop measurements made with a pipeline viscometer located in series with the heat exchange section. D_p is the average diameter of the solid particles as stated by the manufacturer or as determined from sedimentation rates by assuming the particles to be spherical. The subscripts p and L denote properties of the solid particles and of the liquid, respectively.

When the present investigation was initiated, only the studies of Bonilla, et al., and of Orr had been published. Whereas, the data of Orr for water, ethylene glycol, and suspensions of these liquids were all in close agreement with the Sieder and Tate relationship for homogeneous liquids, the water-chalk suspension data of Bonilla, et al.,

differed considerably from the water data reported. This divergence was especially true for the lower range of Reynolds numbers and for the suspensions of higher concentration.

Since this difference might be attributed to stratification in the case of horizontal flow of a liquid-solid suspension, it seemed that further study of other suspensions in horizontal flow was warranted. Therefore, the present investigation was conducted for the horizontal turbulent flow of water and of water suspensions of four solid materials -- precipitated chalk, powdered copper, powdered graphite, and glass beads. With the exception of chalk, these materials were substances which had been studied by Orr. Also, in order to provide a comparative study to that of Orr, the same diameter copper heat transfer pipe was used, and other essential features of the vertical flow apparatus were retained.

In accordance with the presentation of Orr, the heat transfer data obtained in the present investigation were compared with equation 2 by utilizing the suspension thermal conductivity relationship of Tareef, the suspension viscosity relationship proposed by Orr, and the weighted average suspension heat capacity. Data from the above investigations are included with that of the present study in the section devoted to discussion of experimental results.

CHAPTER II

EXPERIMENTAL EQUIPMENT

The design of the heat transfer apparatus incorporated certain features suggested by the apparatus designs of Orr (1952), Bonilla, et al., (1951, 1953), and Miller (1953). The assembled apparatus is shown in Figure 1. A schematic diagram of the arrangement of the equipment is shown in Figure 2. The apparatus consisted essentially of (1) a heat transfer section, (2) a flow-straightening section, (3) suspension mixing chambers, (4) a suspension cooler, (5) a suspension mixing and storage tank, (6) a suspension circulating pump, (7) a suspension rotameter, (8) a pressure drop measuring system, (9) a steam separator, (10) a steam calorimeter, (11) a steam pressure reducing and regulating valve, (12) steam traps, (13) a condensate-measuring system, (14) a potentiometer with terminal box and selector switches, and (15) the necessary piping, valves, pressure gauges, and drain lines. The design and function of each of these principal components will be discussed in detail below.

Three horizontally mounted concentric pipes, joined at the ends by flange and packing connections, composed the heat transfer section. The central pipe, through which the heat transfer fluid passed, was a nominal 3/8-inch standard

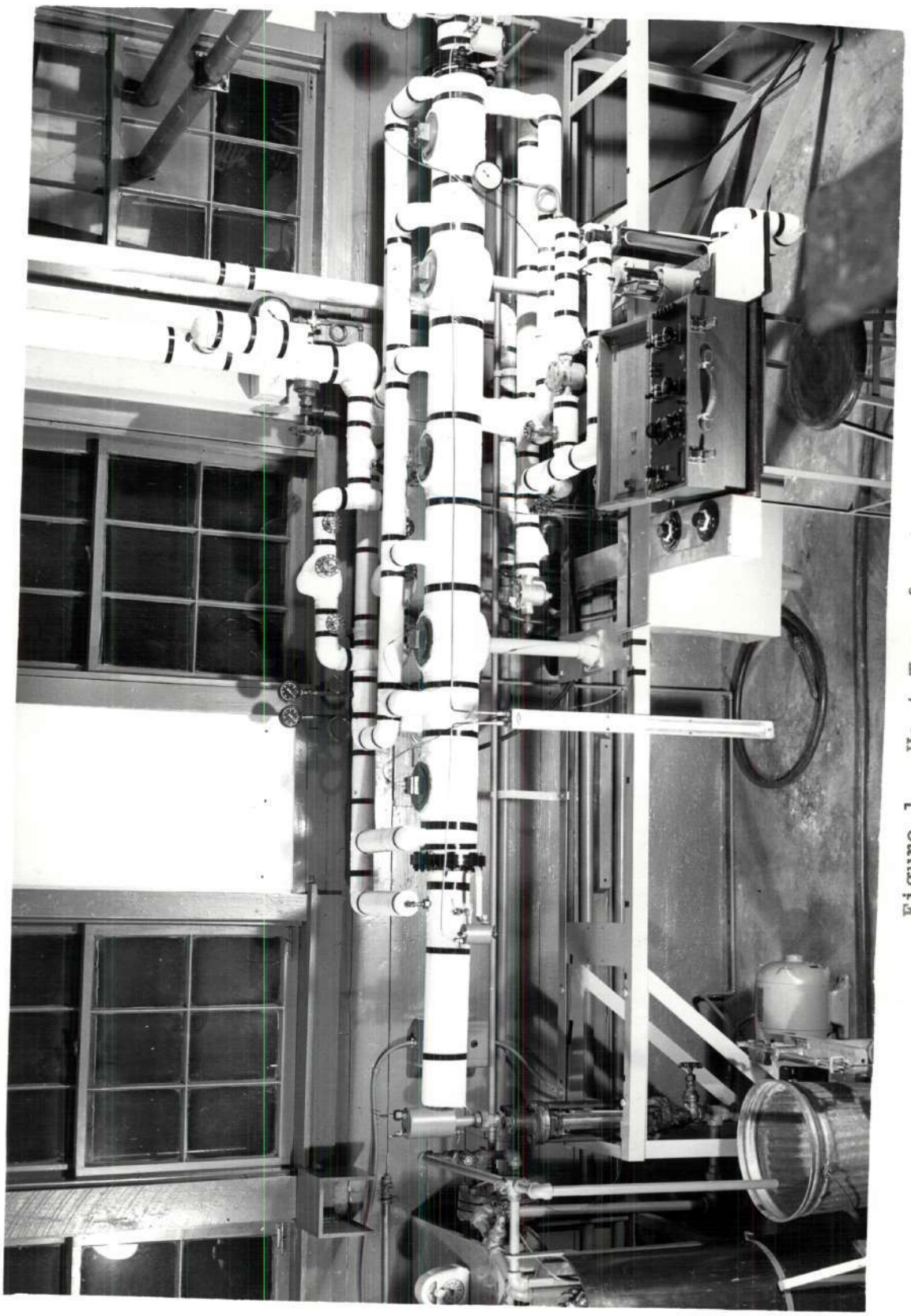

Figure 1. Heat Transfer Apparatus.

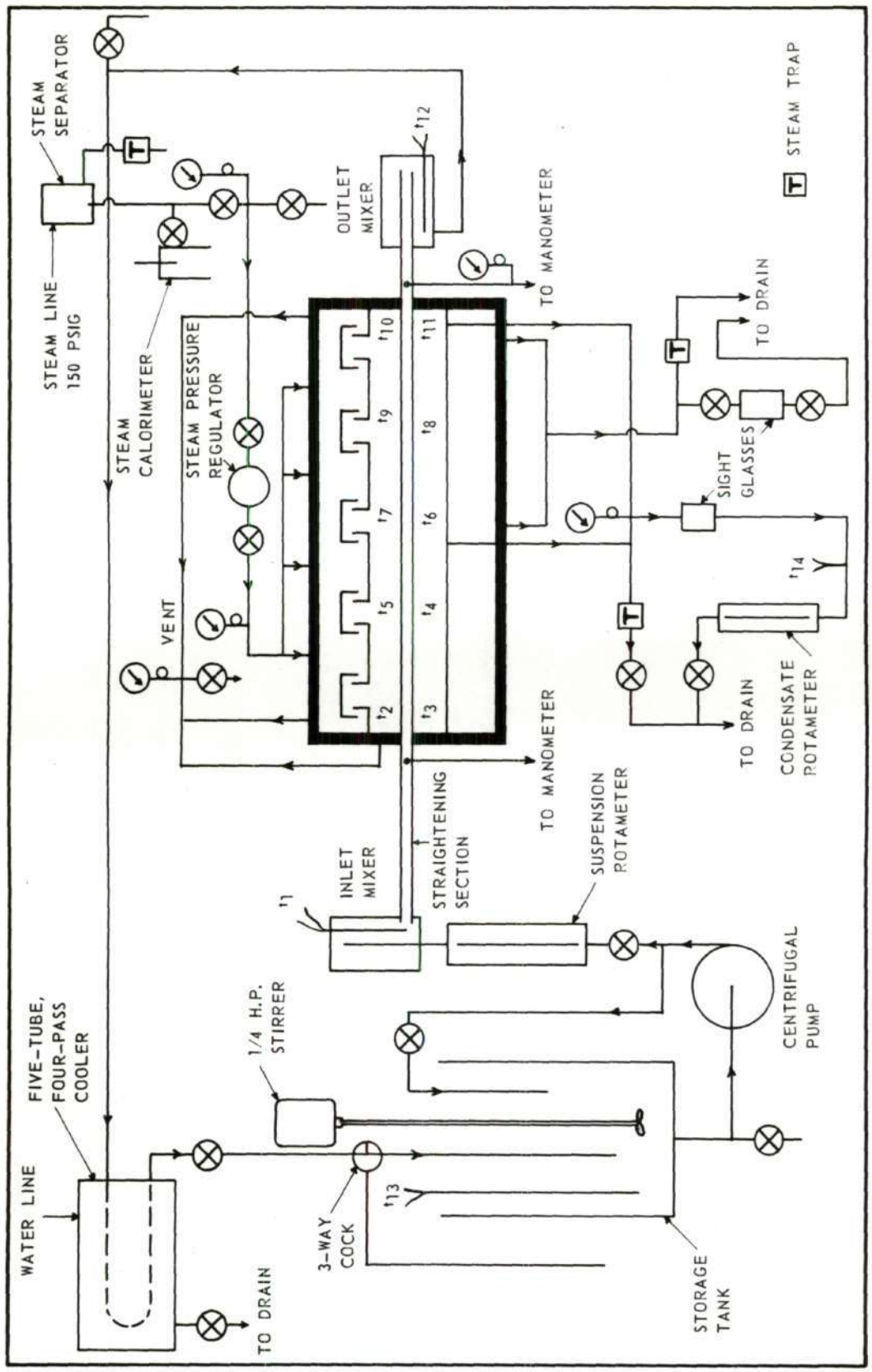

Figure 2. Schematic Diagram of Entire Heat Transfer Apparatus.

I.P.S. copper pipe having a heated length of 8.21 feet. A nominal 2-inch iron pipe, forming the inner annulus, served as a steam jacket for the copper heat transfer pipe. The outer annulus, which acted as a heated guard for the exchanger, consisted of nominal 4-inch iron pipe and fittings. The 2-inch pipe permitted the separation of the steam condensed on the copper pipe from that condensed on the outside wall of the heat transfer section. Details of construction of the packing and flange connections at each end of the exchange section are shown in Figure 3.

Steam entered the top of the outer annulus through four 1/2-inch pipes and passed into the inner annulus through five ports spaced along the top of the 2-inch pipe. Each of these ports consisted of a 1-inch pipe nipple over which was mounted a tin baffle. The baffles prevented condensate from dripping into the steam jacket from the upper wall of the heated guard. The details of construction of the steam ports are shown in Figure 4. A port was located opposite each of the 4-inch pipe plugs shown in Figure 1.

Sixteen copper-constantan thermocouples of Leeds and Northrup Company, Philadelphia, Pennsylvania, No. 24 gauge, double glass wrap, Silicone Resin Impregnated, duplex wire were embedded in the wall of the copper pipe. These thermocouples were located at five points along the heated length of the copper pipe -- near the center, two to four inches

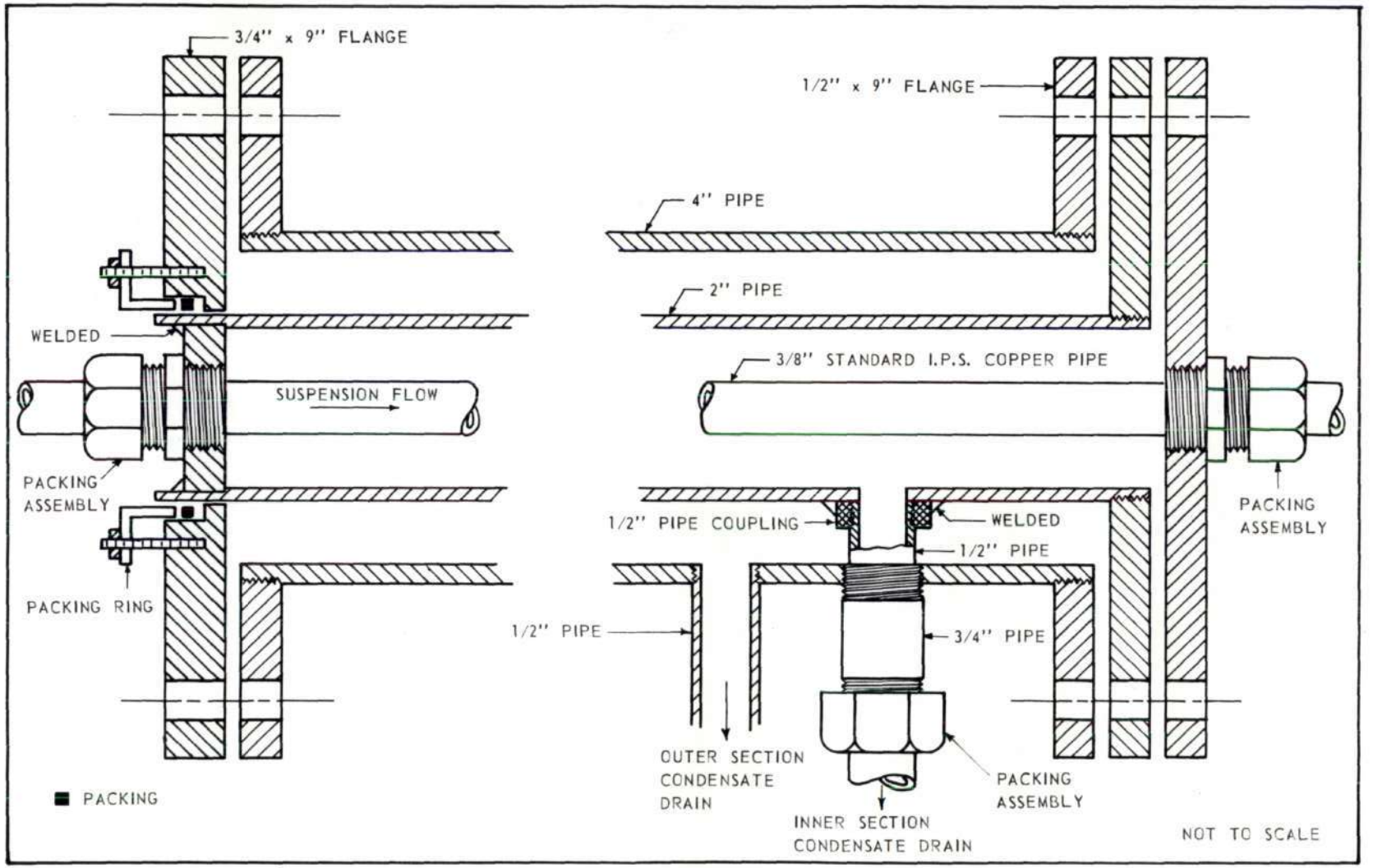

Figure 3. Details of Construction of Packing and Flange Connections at Each End of the Heat Transfer Section; Details of Construction of Condensate Drains at the Outlet End of the Exchange Section.

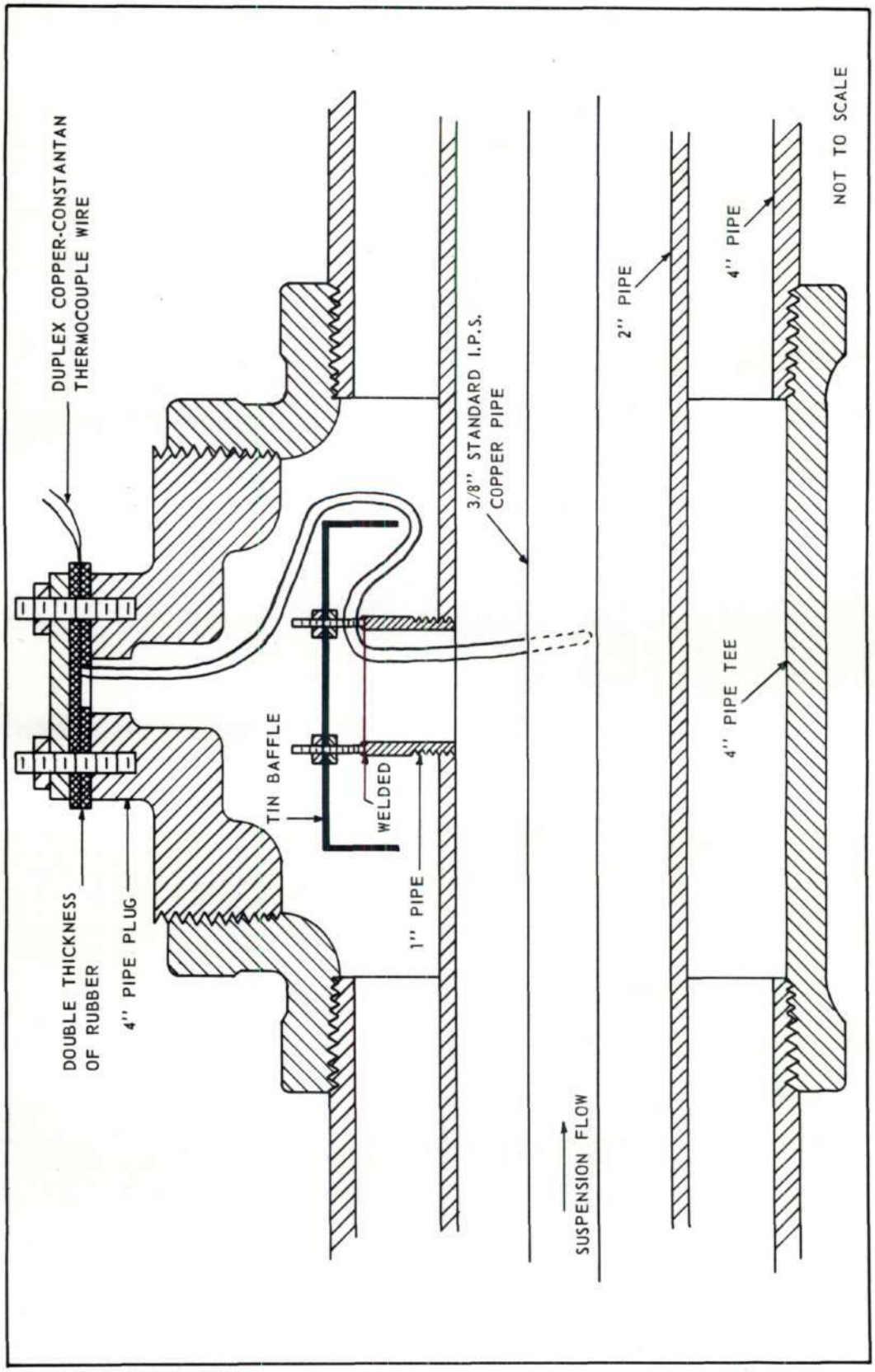

Figure 4. Details of Construction of One of the Five Ports to the Steam Jacket; Method of Withdrawing Thermocouple Leads from the Heat Transfer Section.

from each end, and approximately midway between the center and the end thermocouples. The exact locations of these thermocouples are shown on the data sheet found in the Appendix. At each of the five thermocouple locations, one thermocouple bead was located in the top of the pipe wall and one was located in the bottom of the wall. There was a longitudinal distance of approximately 1/2 of an inch between these two thermocouple positions. Alternate pairs of thermocouples were similarly located near the center and at each end of the copper pipe.

Each thermocouple was installed in the following manner: circumferential grooves, extending half around the pipe, were milled 0.045 of an inch deep and 1/8 of an inch wide; the insulated thermocouple was placed in the groove with the bead at one end and the leads extending out the other; the bead was soldered to the bottom of the groove at the proper point with pure tin; a strip of copper 1/8 of an inch wide was pressed into the unfilled portion of the groove and firmly clamped in place; the strip was soldered with pure tin, and the excess tin and copper were filed down to the level of the original pipe surface. Thus, the thermocouple leads, insulated to the bead, were located in a relatively isothermal zone of the pipe wall for a distance of approximately one inch. The thermocouple leads emerged from the steam jacket through the five steam ports

described above. The method of withdrawing the leads from the outer annulus is shown in Figure 4.

The copper pipe packing assemblies were located 3/16 of an inch vertically off center at each end of the heat transfer section to facilitate drainage of the condensate. This was accomplished by leveling the copper pipe by means of a cathetometer; the offset in the end plates then caused the concentric iron pipes to be tilted in the direction of the fluid outlet end of the exchanger. Separate condensate drains for both annuli were provided near the center and at the outlet end of the heat transfer section. The details of construction of these condensate lines may be seen in Figure 3. Centering screws of calculated lengths were employed at two points in the exchange section to minimize deflection of the copper pipe. The entire exchange section, except for the flange and packing connections, was insulated with standard thickness, 85 per cent magnesia pipe insulation.

At the fluid inlet end of the exchange section, the copper pipe extended 28-1/2 inches outside of the exchanger. This extension served as a flow-straightening section of about fifty-seven pipe diameters. It terminated within a fluid mixing chamber so designed that a complete reversal of flow was achieved. A thermocouple installed near the entrance of the straightening section permitted measurement of the bulk temperature of the fluid entering the heat transfer section. The copper pipe extended 10-3/4 inches

beyond the outlet end of the heat exchange section and terminated inside a mixing chamber where the bulk temperature of the heated fluid was obtained. Both copper pipe extensions were insulated with double-standard thickness, 85 per cent magnesia pipe insulation. The details of construction of the fluid mixing chambers are shown in Figure 5.

Upon leaving the outlet fluid mixing chamber, the fluid passed through two tubes of a five-tube, four-pass heat exchanger having 3/4-inch, No. 18 B.W.G. copper tubes. The exchanger was manufactured by the Bell and Gossett Company, Morton Grove, Illinois. Only two of the five available tubes were used in order that accumulation of solid material in the heat exchanger might be reduced. Tap water was employed as the cooling medium.

The cooled fluid then passed into a stainless steel mixing and storage tank. In flowing to the mixing tank, the fluid passed through a three-way cock which permitted flow rate determination and fluid sampling. The mixing tank was provided with a 1/4-HP, 1,725-rpm fluid mixer manufactured by the Alsop Engineering Corporation, Milldale, Connecticut. A variable transformer was provided so that the degree of agitation might be regulated. A thermocouple mounted in the end of a copper tube was located in the tank, thereby giving a check on the bulk temperature of the fluid entering the heat transfer section.

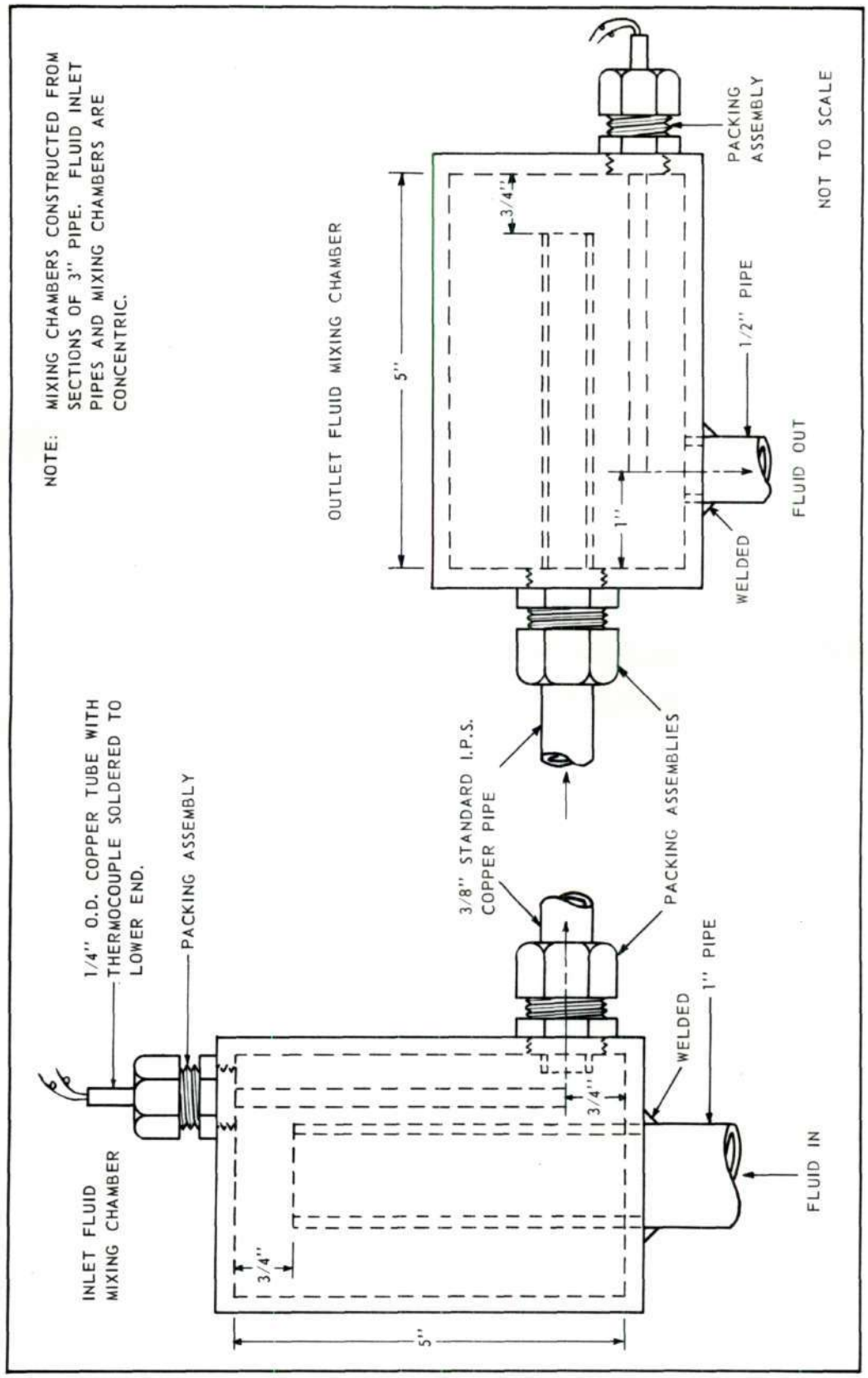

Figure 5. Details of Construction of the Fluid Mixing Chambers.

Fluid was withdrawn from the bottom of the mixing and storage tank by a 1-inch, close-coupled, centrifugal pump having an enclosed type impeller, and driven at 3,450 rpm by a 2-HP motor. The pump was manufactured by the Ingersoll-Rand Company, New York, New York. The stream leaving the pump could be returned directly to the mixing tank or could pass through the heat transfer system.

The fluid which passed through the system went directly from the pump through a 1-1/4-inch rotameter and then to the straightening section described above. The rotameter was the Size No. 7 Universal Model of the Schutte and Koerting Company, Philadelphia, Pennsylvania. During the initial trials with dilute suspensions, the rotameter was useful in determining the relative rates of fluid flow through the system. However, for concentrated suspensions the float position could not be determined. Also, in order to obtain higher flow rates, it was necessary to remove the float from the rotameter. Thereafter, the rotameter tube served to insure the absence of air from the fluid stream.

Measurement of pressure drop accompanying flow of the fluid through the heat exchange section was made with a mercury-filled manometer. Because of the space requirements of the copper pipe packing assemblies, the pressure taps were located 5-3/16 inches outside the inlet to the exchange section and 3-9/16 inches beyond the outlet. Therefore, the pressure drop measurements were made over a distance of

8.93 feet. Details of the method of attaching the taps to the copper pipe are shown by Orr (1952).

As may be seen in Figure 2, steam from the main line first passed through a steam separator. Next, a continuous sample of steam was diverted to a steam calorimeter located on the same line about six feet below the separator. In designing the calorimeter and sampling tube, Orr followed a design recommended in Power Test Codes, ASME Series 1929, Instruments and Apparatus, Part II. The calorimeter temperature was measured with an ASTM-certified thermometer.

Since the pressure in the main steam line averaged about 150 lb./in.^{2} gauge, it was necessary to reduce and regulate the pressure in the heat exchange section. Therefore, a 1/2-inch, No. 960 regulator of the Crane Company, Chicago, Illinois, supplied steam at pressures of from 5 to 30 pounds.

As shown in Figure 2 by the schematic diagram, two streams of condensate were withdrawn from the heat transfer section. In order to maintain a certain pressure within the section, a steam trap or another type of system was required on each condensate exit line. No. 070, 1/2-inch, inverted bucket type steam traps, manufactured by the Strong, Carlisle, and Hammond Company, Cleveland, Ohio, were used. In addition, a valve arrangement permitted the condensate which originated on the copper pipe surface to be discharged either through a steam trap or through a measuring system. The measuring system consisted of a

sight glass, through which the level of this condensate could be viewed, and a Size No. 4, Master-Enclosed, Series 700, rotameter with a viscosity-immune float, manufactured by the Fischer and Porter Company, Hatboro, Pennsylvania. A calibration curve for the entire rotameter range was supplied by the manufacturer. Thus, it was possible to regulate the flow of condensate through the rotameter so that the condensate level stayed within the 1-1/2 inch length of sight glass for a reasonable period of time. A thermocouple installed within this measuring system permitted a determination of the condensate temperature. Condensate from the outer annulus of the heat transfer section could also be diverted through a line containing a sight glass. This was done from time to time as a check on the functioning of the steam trap in this line.

All steam, condensate, and vent lines were insulated with the appropriate size of 85 per cent magnesia pipe insulation.

As mentioned in the preceding discussions, twenty thermocouples were installed in the system. Sixteen of these were employed to measure the copper pipe wall temperatures; two to measure the heat transfer fluid temperatures; one to measure the fluid temperature in the mixing tank; and one to measure the condensate temperature. The leads of each thermocouple were brought through a terminal box to either a double-pole ten point or twelve point Leeds and

Northrup thermocouple selector switch. Potential determinations were made with a Leeds and Northrup No. 8662 Portable Precision Potentiometer and a melting ice reference junction. The potentiometric system was arranged in accordance with principles set forth by Baker, et al., (1953). It was impossible to obtain an accurate calibration of the pipe wall thermocouples after installation in the copper pipe. However, calibrations were obtained for two thermocouples installed in a short segment of copper pipe, for two unmounted thermocouples, and for three thermocouples mounted in small copper tubes for insertion into the fluid or condensate streams. These thermocouples were compared with thermometers calibrated to 0.1 degree Fahrenheit by the National Bureau of Standards. Three measurements of the potential of each thermocouple were made at seven temperatures over the range of 100° F. to 250° F. Upon averaging all of the values of the potentials indicated at each of the seven temperatures, the maximum difference between measured potential and average potential at each temperature was 32 microvolts or less. Therefore, a graph of average potential for all of the thermocouples versus temperature was utilized in determining the pipe wall temperatures. A separate graph of average potential for the fluid and condensate thermocouples, which were in very close agreement at each temperature, was also made. This latter calibration curve

was used only in the determination of temperatures in the fluid mixing chambers and in the condensate line. These two calibration curves, which were approximately parallel to the standard copper-constantan thermocouple potential and temperature relationship given by Shenker, et al., (1951), were within the standard limits of error specified for the wire by the manufacturer. The calibration data are given in the Appendix.

Bourdon gauges were installed at several points in the heat transfer apparatus to measure steam pressure and at one point to indicate the pressure on the heated fluid. Steam gauges were located on the main line near the calorimeter, on the reduced-pressure steam line, on the inner annulus condensate exit line, and on the exchange section air vent line. A gauge located at the solid material trap in the low pressure line of the pressure drop measuring system served to insure that the minimum pressure on the fluid in the exchange section was sufficient to prevent boiling. This gauge was also useful in establishing the relative rates of fluid flow through the heat exchange section. All gauges were calibrated with a dead-weight gauge tester prior to installation.

Valves and cocks were installed in the apparatus to control the flow of the heat transfer fluid, steam, or cooling water and to permit draining and cleaning of the system.

CHAPTER III

EXPERIMENTAL PROCEDURE

During the period of apparatus adjustment and technique development, a definite experimental procedure was established. Although several runs were made with pure water as the heat transfer fluid, the following discussion will describe the procedure that was followed for suspensions of solid material in water.

A period of from four to five hours was required for the complete investigation of a suspension of constant concentration. Therefore, in order to allow time for draining and flushing the system, not more than two or three concentrations of a certain suspension were studied during a single period of operation.

At the beginning of a series of runs, the tank was partially filled with water, the circulating pump was started, the cock in the fluid line from the heat exchange section was opened to the drain, and fresh water was added to the tank at the rate at which the system was being drained. As soon as the water in the system was clear, the drain cock was closed, and the tank was filled with water to the desired level. Then, the stirrer in the tank was started, and the flow of water through the system was set

at a moderate rate. Preparatory to the admission of steam into the heat exchange section, the vent lines were opened; both condensate lines from the exchange section were routed through steam traps; the main steam line was freed of condensate; the drain from the steam separator was opened in order to free the main line of future condensate; and the flow of cooling water to the fluid cooler was started. Finally, steam was admitted to the heat exchange section, and the valve to the steam calorimeter was opened.

Through reduction of the cooling water rate, the water in the system was brought almost to the boiling temperature in order to expel absorbed gases. Then, the water temperature was brought to a lower level, and the desired quantity of solid material was added to the mixing tank. After thorough mixing of the solid-liquid suspension had been attained, the pressure drop measuring system and the fluid pressure gauge were opened to the pressure in the system. The suspension flow rate was then adjusted to the desired range, as indicated by readings of pressure drop and fluid pressure.

When the apparatus had adjusted itself to the new temperature conditions, the steam pressure in the exchange section was readjusted to the desired value, and the suspension flow rate and temperature were reset, if necessary, by manipulation of the fluid and cooling water valves. The

flow of condensate from the inner annulus of the exchanger was then routed through the condensate measuring system, and the valve in this line was adjusted so that the condensate level remained within the sight glass. During the next hour, the suspension temperatures were periodically checked, and the condensate level was kept within the sight glass by adjustment of the valve.

When the system had reached a state of equilibrium, as indicated by the constancy of the temperatures within the fluid mixing chambers, the following data were recorded: suspension inlet and outlet temperatures, copper pipe temperatures, condensate temperature, mixing tank temperature, condensate rotameter reading, calorimeter temperature, main line and exchange section steam pressures, pressure on the fluid, fluid pressure drop through the exchanger, and barometric pressure. Immediately after these readings had been recorded, the three-way cock in the fluid line was utilized to obtain suspension samples and to measure suspension flow rate. A half-gallon sample of the suspension obtained at this time was later weighed in a 2-liter graduated cylinder for the density determination; a sample contained in a 250-milliliter or a 500-milliliter graduated cylinder was later used to determine the settled bed volume of the suspension. Suspension flow rate was determined by weighing the amount of suspension collected during a certain time

interval. This quantity of suspension was returned to the mixing tank, and preparations were made for the next run.

A series of runs with a suspension of constant concentration was usually begun with the run of highest suspension flow rate, and the flow was decreased for each of the three or four succeeding runs. Also, the lowest suspension concentration was the first studied, and more solid material was added to the tank when it was desired to investigate another concentration of the same suspension. Therefore, at the completion of a run, either the flow rate was reduced, or more solid material was added to the tank and the flow was again increased to the highest rate desired.

During the interval between periods of operation, and when investigations were to be conducted upon suspensions of another solid material, the system was cleaned by circulating a suspension of glass beads and water for several hours. This treatment removed any accumulation of solid material from the wall of the copper heat transfer pipe. This was evidenced by the fact that subsequent runs employing pure water were in agreement with the initial water runs of this investigation, as well as with the established correlation for pure liquids. Also, visual inspection of the copper pipe wall following one such cleaning showed the pipe wall to be in the same clean condition as when the apparatus was being constructed. As a final step in the cleaning

procedure, water was circulated through the system for several hours, and the manometer lines and traps were filled with clean water.

CHAPTER IV

EXPERIMENTAL DATA

General fluid system information for all runs is given in Table I. The experimental heat transfer data are found in Table II. The form of the experimental data sheet is represented in Appendix II. Copies of the original data sheets are on file at the Price Gilbert Library of the Georgia Institute of Technology.

For each run the pipe wall center temperatures were plotted versus the corresponding thermocouple locations. The data were represented satisfactorily for each run by a straight line through the points. The inlet and outlet pipe wall center temperatures listed in Table II are the values obtained by extrapolation to the lines representing graphically the extremities of the heated portion of the copper pipe. Figure 10 in Appendix II shows the pipe wall temperature distribution for a typical run.

Although not used in the calculations of this investigation, measurements of the fluid pressure drop due to friction are included in Table II.

Treatment of the experimental heat transfer data is illustrated by the sample calculation presented in Appendix II. The calculated results for all of the runs are given in

Table III, and the dimensionless groups of equation 2 are given in Table IV. Discussion of the calculated heat transfer data is reserved for the next chapter.

TABLE I. GENERAL FLUID SYSTEM INFORMATION

Run No.	Fluid System	Weight Per Cent Solid Material	Volume Per Cent Solid Material
1	Water	0	0
2	"	0	0
3	"	0	0
4	Water and glass beads	4.70	1.88
5	"	4.70	1.88
6	"	4.70	1.88
7	"	4.70	1.88
8	"	4.70	1.88
9	Water	0	0
10	Water and glass beads	15.4	6.55
11	"	15.4	6.55
12	"	15.4	6.55
13	"	15.4	6.56
14	"	15.4	6.58
15	"	27.4	12.7
16	"	27.4	12.7
17	"	27.4	12.7
18	"	27.4	12.7
19	"	31.7	15.1
20	"	31.7	15.1
21	"	31.7	15.2
22	"	31.7	15.2
23	Water	0	0
24	Water and graphite	5.55	2.78
25	"	5.55	2.78
26	"	5.55	2.78
27	"	5.55	2.78
28	"	5.55	2.79
29	Water	0	0
30	Water and graphite	16.0	8.49
31	"	16.0	8.49
32	"	16.0	8.49
33	"	16.0	8.49
34	"	16.0	8.48
35	"	28.5	16.1
36	"	28.5	16.1

(Continued)

TABLE I. GENERAL FLUID SYSTEM INFORMATION
(Concluded)

Run No.	Fluid System	Weight Per Cent Solid Material	Volume Per Cent Solid Material
37	Water and graphite	28.5	16.1
38	"	28.5	16.1
39	"	28.5	16.3
40	"	32.5	18.8
41	"	32.5	18.8
42	"	32.5	18.8
43	"	32.5	18.9
44	Water	0	0
45	Water and glass beads	14.1	6.02
46	"	14.1	5.98
47	"	14.1	5.98
48	Water	0	0
49	Water and chalk	4.99	1.84
50	"	4.99	1.84
51	"	4.99	1.84
52	"	4.99	1.84
53	"	4.99	1.85
54	"	13.9	5.42
55	"	13.9	5.44
56	"	13.9	5.45
57	"	13.9	5.48
58	"	13.9	5.49
59	Water and copper	3.55	0.40
60	"	3.55	0.40
61	"	3.55	0.40
62	"	3.55	0.40
63	"	3.55	0.40
64	"	15.3	1.93
65	"	15.3	1.93
66	"	15.3	1.93
67	"	23.8	3.28
68	"	23.8	3.28
69	"	23.8	3.28
70	"	28.1	4.08
71	"	28.1	4.08
72	Water and glass beads	13.6	5.74

TABLE II. EXPERIMENTAL HEAT TRANSFER DATA

Run No.	Rate of Fluid Flow (lb./min.)	Fluid Pressure Drop in Exchange Section (in. Hg)	Minimum Pressure on Fluid (psia)	Main Steam Line Pressure (psia)	Barometric Pressure (in. Hg)	Calorimeter Temperature (°F.)	Steam Condensed (lb./min.)	Approximate Steam Pressure in Exchange Section (psia)	Temperature of Leaving Condensate (°F.)	Pipe Wall Center Temperature		Fluid Temperature	
										Inlet (°F.)	Outlet (°F.)	Inlet (°F.)	Outlet (°F.)
1	44.6	4.6	18.8	157	29.3	292.3	2.36	30.5	249.2	232.8	243.8	172.5	218.3
2	52.3	5.6	19.1	161	29.3	293.3	2.66	26.0	238.4	220.7	231.5	156.3	204.2
3	66.2	9.4	22.1	164	29.0	294.0	2.73	22.7	230.8	215.0	223.9	161.5	200.5
4	87.9	16.6	-	165	29.0	294.3	2.86	20.7	226.5	208.8	219.0	166.1	198.0
5	76.1	13.0	24.7	164	29.0	294.0	2.84	21.7	228.5	211.9	221.1	163.5	199.8
6	66.2	9.6	21.8	163	29.0	293.8	2.78	22.6	230.8	213.6	224.2	160.7	201.9
7	55.3	7.5	19.7	166	29.0	294.5	2.69	23.7	232.6	216.0	226.6	157.3	203.3
8	44.8	4.8	17.4	164	29.0	294.0	2.52	25.1	237.7	219.4	229.7	152.7	206.3
9	80.5	13.0	25.9	163	29.1	293.8	2.78	26.8	240.4	224.0	232.5	176.5	208.8
10	89.4	16.3	28.1	165	29.1	294.3	2.83	26.7	239.7	222.0	233.2	178.2	211.0
11	80.5	13.1	25.0	163	29.1	293.8	2.76	27.1	241.3	223.5	235.0	176.1	212.4
12	66.7	9.4	21.6	165	29.1	294.3	2.69	27.9	243.1	225.9	237.2	172.6	214.6
13	56.4	7.0	19.4	165	29.1	294.3	2.57	28.8	244.7	228.0	239.2	168.2	216.4
14	36.4	3.4	16.9	164	29.1	294.0	2.48	29.5	245.7	229.3	243.1	147.5	215.9
15	90.0	14.2	26.4	164	29.1	294.0	2.83	25.5	237.8	218.8	230.5	167.3	205.9
16	80.2	11.4	23.7	165	29.1	294.3	2.78	26.3	239.4	220.3	233.3	165.0	207.5
17	65.0	7.8	20.3	162	29.1	293.5	2.68	27.4	241.9	223.4	236.3	160.1	209.9
18	43.5	3.8	16.9	161	29.1	293.3	2.43	29.9	246.8	231.2	241.4	149.8	214.3
19	92.3	14.8	26.7	162	29.1	293.5	2.87	32.0	250.1	232.9	243.6	180.3	217.8
20	78.9	10.9	22.9	165	29.1	294.3	2.75	33.1	252.7	235.4	246.4	176.9	219.5
21	62.9	7.5	19.4	167	29.1	294.8	2.06	22.1	230.4	216.2	225.7	158.7	200.7
22	43.6	4.3	16.4	166	29.1	294.5	1.90	24.1	234.4	219.6	231.5	146.4	201.4
23	61.8	8.3	20.9	163	29.2	293.8	2.67	23.4	232.3	215.1	224.7	157.8	197.8
24	88.0	15.3	27.6	164	29.2	294.0	3.01	25.1	236.1	217.2	227.6	168.3	202.4
25	78.0	12.3	24.6	160	29.2	293.0	2.98	25.5	237.3	218.5	229.8	166.3	203.8
26	65.3	9.0	21.5	163	29.2	293.8	2.84	26.8	240.9	221.4	233.6	163.2	206.7
27	52.9	6.2	19.1	162	29.2	293.5	2.71	27.7	242.9	224.1	236.2	155.8	207.8
28	34.9	3.1	16.3	162	29.2	293.5	2.71	30.3	248.6	230.4	242.5	142.7	213.1
29	36.3	3.3	16.4	165	29.1	294.3	2.42	25.9	238.3	223.0	233.2	139.7	201.8
30	92.9	15.6	28.2	163	29.0	293.8	2.78	23.0	231.5	213.2	223.8	165.9	199.2
31	67.4	9.1	21.4	164	29.0	294.0	2.64	24.3	234.2	217.6	227.6	160.8	202.8
32	78.7	12.3	25.0	164	29.0	294.0	2.79	23.4	232.3	215.0	225.2	163.8	200.6
33	54.0	6.2	18.9	167	29.0	294.8	2.50	25.8	237.9	221.6	231.8	157.0	205.8
34	32.6	3.0	16.6	163	29.0	293.8	2.02	29.0	246.5	231.7	242.9	150.7	216.6
35	93.7	15.8	28.3	166	28.9	294.5	2.66	26.0	238.6	222.9	231.5	173.9	207.1
36	83.4	12.5	25.2	167	28.9	294.8	2.52	29.2	245.5	230.7	239.0	178.8	214.2

(Continued)

TABLE II. EXPERIMENTAL HEAT TRANSFER DATA (Concluded)

Run No.	Rate of Fluid Flow (lb./min.)	Fluid Pressure Drop in Exchange Section (in. Hg)	Minimum Pressure on Fluid (psia)	Main Steam Line Pressure (psia)	Barometric Pressure (in. Hg)	Calorimeter Temperature (°F.)	Steam Condensed (lb./min.)	Approximate Steam Pressure in Exchange Section (psia)	Temperature of Leaving Condensate (°F.)	Pipe Wall Center Temperature		Fluid Temperature	
										Inlet (°F.)	Outlet (°F.)	Inlet (°F.)	Outlet (°F.)
37	69.1	9.3	22.1	164	28.9	294.0	2.38	30.0	248.0	232.7	241.0	174.7	215.0
38	55.3	6.5	19.5	162	28.9	293.5	2.22	30.4	248.4	234.0	243.2	166.9	212.8
39	39.7	3.7	17.5	166	28.9	294.5	1.65	25.4	237.5	228.6	232.6	142.6	190.6
40	94.0	12.2	28.8	163	28.9	293.8	2.54	29.6	246.2	232.0	238.4	176.5	209.8
41	107.3	-	32.0	162	28.9	293.5	2.58	27.1	240.6	226.2	233.1	177.7	207.5
42	77.1	-	24.7	163	28.9	293.8	2.41	29.9	247.8	232.4	240.7	171.4	209.5
43	66.8	-	22.6	166	28.9	294.5	2.37	30.2	248.0	233.7	241.7	165.2	207.5
44	27.6	2.0	15.3	167	29.1	294.8	1.97	23.4	233.8	220.0	229.2	132.2	198.2
45	29.5	2.4	15.3	164	29.1	294.0	1.73	26.4	239.7	228.2	231.3	131.5	191.1
46	61.3	7.8	20.4	165	29.1	294.3	2.77	26.6	240.1	223.5	231.5	157.2	204.7
47	101.8	20.0	31.8	163	29.1	293.8	3.02	23.8	232.3	215.5	220.5	165.8	197.5
48	100.6	19.9	32.4	164	29.0	294.0	3.07	24.1	233.6	217.5	222.1	169.3	198.4
49	99.9	20.0	31.9	164	29.0	294.0	3.08	24.5	234.0	218.8	223.0	170.9	201.3
50	88.7	16.1	28.1	162	29.0	293.5	3.02	26.3	235.6	220.0	225.0	168.6	202.1
51	76.6	12.3	24.5	162	29.0	293.5	2.94	25.5	237.4	221.6	227.1	165.5	203.1
52	58.8	7.4	20.0	160	29.0	293.0	2.82	27.0	242.0	225.7	233.0	159.9	205.9
53	24.8	1.9	15.1	160	29.0	293.0	1.84	23.3	233.4	221.3	230.0	131.3	201.0
54	99.3	19.7	31.2	158	29.1	292.5	2.73	25.8	238.0	224.1	228.8	179.0	207.5
55	67.6	15.9	22.2	162	29.1	293.5	2.53	27.3	242.5	222.5	238.5	167.4	206.7
56	56.4	11.8	20.1	162	29.1	293.5	2.28	29.5	246.6	229.0	245.0	163.3	204.9
57	45.4	7.0	17.8	166	29.1	294.5	1.82	23.6	233.6	222.9	230.7	145.9	187.0
58	21.0	1.9	14.3	164	29.1	294.0	1.02	27.6	242.2	236.2	242.4	137.3	187.8
59	100.2	19.9	32.0	162	29.0	293.5	3.26	23.4	230.7	214.0	217.9	164.4	196.3
60	89.7	16.0	28.0	160	29.0	293.0	3.23	24.2	233.3	215.2	221.2	162.7	198.3
61	76.7	12.2	24.1	163	29.0	293.8	3.16	24.8	235.0	216.2	223.8	159.7	200.2
62	58.4	7.2	19.5	163	29.0	293.8	2.95	25.9	237.4	220.4	228.1	152.4	202.6
63	19.9	2.1	17.3	162	29.0	293.5	2.06	32.6	253.5	239.9	248.7	130.1	220.5
64	106.6	19.6	32.1	160	29.1	293.0	3.22	23.6	230.8	214.5	218.7	163.5	196.7
65	94.5	15.0	27.6	161	29.1	293.3	3.16	24.0	232.4	214.8	221.8	161.4	198.4
66	74.5	10.2	22.5	160	29.1	293.0	3.02	24.8	234.4	217.1	224.8	156.1	200.0
67	114.1	19.8	33.3	160	29.1	293.0	3.25	23.5	231.0	213.4	219.0	162.9	195.9
68	100.6	15.0	28.1	160	29.1	293.0	3.10	23.8	232.2	214.0	221.4	159.9	197.5
69	77.4	10.0	22.6	159	29.1	292.8	2.94	25.0	235.5	217.5	225.0	155.3	200.1
70	120.0	20.1	33.9	160	29.1	293.0	3.19	23.5	231.7	212.5	217.2	159.9	192.6
71	93.3	13.1	26.1	160	29.1	293.0	3.08	24.6	233.8	215.8	222.2	155.7	196.8
72	108.6	-	-	159	28.8	292.8	3.07	25.0	236.3	208.2	215.4	161.0	189.6

TABLE III. CALCULATED HEAT TRANSFER DATA

Run No.	Fluid Heat Capacity (Btu / lb., °F.)	Heat to Fluid (Btu / min.)	Heat from Steam (Btu / min.)	Heat Balance Error (Based on Heat to Fluid) (Per Cent	Inside Pipe Surface Temperature Inlet (°F.)	Inside Pipe Surface Temperature Outlet (°F.)	Logarithmic Mean Temperature Difference (°F.)	Heat Transfer Coefficient (Btu / hr., ft.², °F.)	Average Ratio of Bed Volume to Suspension Volume	Sedimentation Volume Fraction Solids	Fluid Viscosity (lb. / hr., ft.)	Fluid Thermal Conductivity (Btu / hr., ft.², (°F. / ft.))
1	1.005	2050	2290	11.7	231.0	242.0	38.5	3000	0	0	0.760	0.393
2	1.003	2510	2620	4.4	218.4	229.2	40.8	3480	0	0	0.838	0.390
3	1.003	2590	2710	4.6	212.7	221.6	33.9	4310	0	0	0.835	0.390
4	0.969	2720	2840	4.4	206.4	216.6	28.1	5450	0.0457	0.510	0.887	0.393
5	0.969	2680	2820	5.2	209.5	218.7	30.5	4950	0.0457	0.510	0.889	0.393
6	0.969	2640	2750	4.2	211.2	221.8	32.9	4530	0.0457	0.510	0.891	0.393
7	0.969	2470	2660	7.7	213.8	224.4	35.9	3870	0.0457	0.510	0.896	0.393
8	0.969	2330	2480	6.4	217.3	227.6	41.3	3180	0.0457	0.510	0.902	0.393
9	1.005	2610	2730	4.6	221.7	230.2	31.8	4630	0	0	0.772	0.392
10	0.892	2620	2780	6.1	219.7	230.9	29.4	5020	0.143	0.510	0.977	0.402
11	0.892	2610	2710	3.8	221.2	232.7	31.1	4730	0.143	0.510	0.980	0.402
12	0.892	2500	2630	5.2	223.7	235.0	33.4	4220	0.143	0.510	0.983	0.402
13	0.892	2420	2510	3.7	225.8	237.0	36.0	3800	0.143	0.510	0.992	0.402
14	0.891	2220	2420	9.0	227.3	241.1	47.4	2640	0.143	0.510	1.07	0.400
15	0.803	2790	2790	0	216.3	228.0	33.8	4660	0.308	0.510	1.34	0.411
16	0.803	2740	2740	0	217.8	230.8	36.1	4280	0.308	0.510	1.35	0.411
17	0.803	2600	2620	0.8	221.1	234.0	39.7	3690	0.308	0.510	1.36	0.410
18	0.803	2250	2370	5.3	229.2	239.4	47.1	2700	0.308	0.510	1.39	0.410
19	0.773	2670	2780	4.1	230.5	241.2	35.1	4290	0.509	0.510	1.40	0.416
20	0.772	2590	2670	3.1	233.1	244.1	38.2	3630	0.509	0.510	1.41	0.416
21	0.771	2040	2040	0	214.4	223.9	37.1	3100	0.509	0.510	1.60	0.413
22	0.771	1850	1870	1.1	217.9	229.8	46.7	2230	0.509	0.510	1.66	0.412
23	1.003	2480	2640	6.5	212.9	222.5	37.9	3690	0	0	0.852	0.390
24	0.961	2880	2970	3.1	214.6	225.0	33.0	4930	0.182	0.264	0.989	0.424
25	0.961	2810	2940	4.6	216.0	227.3	35.0	4530	0.182	0.264	0.991	0.424
26	0.961	2730	2780	1.8	219.0	231.2	38.0	4050	0.182	0.264	0.993	0.424
27	0.960	2640	2650	0.4	221.7	233.8	42.9	3470	0.182	0.264	1.01	0.423
28	0.960	2360	2640	11.9	228.3	240.4	51.0	2610	0.182	0.264	1.04	0.423
29	1.002	2260	2380	5.3	221.0	231.2	51.0	2500	0	0	0.895	0.388
30	0.879	2720	2750	1.1	210.8	221.4	32.2	4760	0.467	0.264	1.66	0.498
31	0.879	2490	2610	4.8	215.4	225.4	36.3	3870	0.467	0.264	1.67	0.498
32	0.879	2550	2760	8.2	212.7	222.9	33.9	4240	0.467	0.264	1.67	0.498
33	0.879	2320	2460	6.0	219.5	229.7	40.1	3260	0.467	0.264	1.68	0.497
34	0.879	1890	1970	4.2	230.0	241.2	46.7	2280	0.467	0.264	1.65	0.498
35	0.783	2440	2620	7.4	220.7	229.3	33.0	4160	0.749	0.264	4.27	0.614
36	0.784	2320	2460	6.0	228.6	236.9	34.5	3790	0.749	0.264	4.11	0.615

(Continued)

TABLE III. CALCULATED HEAT TRANSFER DATA (Concluded)

Run No.	Fluid Heat Capacity (Btu / lb., °F.)	Heat to Fluid (Btu / min.)	Heat from Steam (Btu / min.)	Heat Balance Error (Based on Heat to Fluid) (Per Cent)	Inside Pipe Surface Temperature Inlet (°F.)	Inside Pipe Surface Temperature Outlet (°F.)	Logarithmic Mean Temperature Difference (°F.)	Heat Transfer Coefficient (Btu / hr., ft.², °F.)	Average Ratio of Bed Volume to Suspension Volume	Sedimentation Volume Fraction Solids	Fluid Viscosity (lb. / hr., ft.)	Fluid Thermal Conductivity (Btu / hr., ft.², °F. / ft.)
37	0.784	2180	2320	6.4	230.7	239.0	37.8	3260	0.749	0.264	4.15	0.615
38	0.783	1990	2160	8.5	232.2	241.4	44.4	2520	0.749	0.264	4.29	0.614
39	0.779	1480	1620	9.5	227.3	231.3	60.0	1400	0.749	0.264	5.19	0.610
40	0.752	2360	2470	4.7	229.9	236.3	38.4	3460	0.810	0.264	7.28	0.661
41	0.752	2410	2530	5.0	224.0	230.9	33.6	4040	0.810	0.264	7.32	0.660
42	0.752	2210	2350	6.3	230.4	238.7	42.4	2940	0.810	0.264	7.45	0.660
43	0.751	2120	2310	9.0	231.8	239.8	47.4	2520	0.810	0.264	7.70	0.660
44	1.002	1830	1950	6.6	218.4	227.6	52.8	1950	0	0	0.933	0.387
45	0.899	1580	1700	7.6	226.8	229.9	62.9	1420	0.342	0.510	1.20	0.395
46	0.900	2620	2720	3.8	221.2	229.2	41.1	3590	0.342	0.510	1.05	0.399
47	0.900	2900	2990	3.1	212.9	217.9	31.9	5130	0.342	0.510	1.04	0.399
48	1.004	2940	3030	3.1	214.9	219.5	31.8	5210	0	0	0.819	0.391
49	0.965	2930	3040	3.8	216.2	220.4	30.3	5530	0.231	0.0765	1.29	0.391
50	0.965	2870	2980	3.8	217.4	222.4	32.5	4970	0.231	0.0765	1.30	0.391
51	0.964	2780	2890	4.0	219.1	224.6	35.1	4460	0.231	0.0765	1.31	0.391
52	0.964	2610	2760	5.7	223.4	230.7	41.2	3570	0.231	0.0765	1.32	0.391
53	0.963	1660	1820	9.6	219.8	228.5	52.2	1800	0.231	0.0765	1.48	0.387
54	0.895	2530	2680	5.9	221.8	226.5	29.3	4880	0.511	0.0765	2.79	0.393
55	0.894	2380	2480	4.2	220.4	236.4	40.2	3330	0.511	0.0765	2.91	0.392
56	0.894	2100	2220	5.7	227.0	243.0	49.8	2380	0.511	0.0765	2.96	0.391
57	0.892	1670	1800	7.8	221.4	229.2	57.2	1640	0.511	0.0765	3.35	0.388
58	0.892	946	999	5.6	235.4	241.6	73.7	724	0.511	0.0765	3.45	0.387
59	0.971	3100	3230	4.2	211.2	215.1	30.7	5700	0.0185	0.541	0.850	0.395
60	0.971	3100	3190	2.9	212.4	218.4	32.7	5350	0.0185	0.541	0.850	0.395
61	0.971	3020	3120	3.3	213.5	221.1	34.8	4890	0.0185	0.541	0.852	0.395
62	0.971	2840	2900	2.1	217.9	225.6	40.6	3950	0.0185	0.541	0.866	0.394
63	0.971	1750	1990	13.7	238.3	247.1	58.1	1700	0.0185	0.541	0.879	0.394
64	0.864	3060	3190	4.3	211.8	216.0	31.6	5460	0.0554	0.541	0.896	0.413
65	0.864	3020	3130	3.6	212.1	219.1	33.5	5090	0.0554	0.541	0.897	0.413
66	0.864	2830	2980	5.3	214.6	222.3	37.5	4250	0.0554	0.541	0.908	0.413
67	0.787	2960	3220	8.8	210.7	216.3	32.2	5190	0.0840	0.541	0.943	0.430
68	0.787	2980	3070	3.0	211.3	218.7	34.1	4920	0.0840	0.541	0.947	0.429
69	0.787	2730	2900	6.2	215.1	222.6	38.2	4030	0.0840	0.541	0.954	0.429
70	0.747	2930	3150	7.5	209.9	214.6	34.1	4850	0.102	0.541	0.992	0.439
71	0.747	2860	3050	6.6	213.2	219.6	37.5	4310	0.102	0.541	0.992	0.439
72	0.903	2810	3020	7.5	205.7	212.9	32.8	4820	-	0.510	1.07	0.398

TABLE IV. CALCULATED DIMENSIONLESS GROUPS

Run No.	$(\frac{DG}{\mu})$	$(\frac{hD}{k})$	$(\frac{C_p\mu}{k})$	$(\frac{\mu}{\mu_w})$	$\frac{(\frac{hD}{k})}{(\frac{C_p\mu}{k})^{1/3}(\frac{\mu}{\mu_w})^{0.14}}$
1	109,000	316	1.95	1.28	245
2	116,000	368	2.16	1.31	274
3	147,000	456	2.15	1.25	342
4	184,000	572	2.19	1.20	429
5	159,000	519	2.19	1.23	389
6	138,000	476	2.20	1.25	355
7	114,000	407	2.21	1.27	302
8	92,000	333	2.22	1.31	246
9	193,000	488	1.98	1.22	378
10	169,000	514	2.17	1.20	387
11	152,000	485	2.17	1.22	364
12	126,000	433	2.18	1.24	324
13	105,000	390	2.20	1.26	290
14	63,300	272	2.37	1.38	195
15	124,000	468	2.63	1.25	329
16	110,000	430	2.64	1.26	301
17	88,500	371	2.66	1.30	259
18	58,200	271	2.71	1.37	186
19	122,000	426	2.60	1.24	301
20	104,000	380	2.61	1.27	267
21	73,000	309	2.97	1.28	208
22	48,700	223	3.10	1.37	147
23	134,000	391	2.19	1.29	290
24	165,000	479	2.24	1.24	355
25	146,000	441	2.25	1.25	326
26	122,000	394	2.25	1.28	290
27	96,700	338	2.30	1.33	247
28	62,200	255	2.36	1.41	182
29	75,100	266	2.31	1.42	191
30	104,000	395	2.94	1.23	268
31	74,800	321	2.95	1.27	216
32	87,500	351	2.94	1.25	238
33	59,700	270	2.96	1.31	181
34	36,600	189	2.92	1.37	127
35	40,600	280	5.45	1.24	154
36	37,600	254	5.23	1.24	142

(Continued)

TABLE IV. CALCULATED DIMENSIONLESS GROUPS
(Concluded)

Run No.	$(\frac{DG}{\mu})$	$(\frac{hD}{k})$	$(\frac{C_p\mu}{k})$	$(\frac{\mu}{\mu_w})$	$\frac{\frac{hD}{k}}{(\frac{C_p\mu}{k})^{1/3}(\frac{\mu}{\mu_w})^{0.14}}$
37	30,800	219	5.29	1.27	121
38	23,900	170	5.47	1.32	92.6
39	14,200	94.4	6.63	1.49	47.5
40	23,900	216	8.29	1.27	103
41	27,200	252	8.34	1.23	121
42	19,200	184	8.48	1.30	86.7
43	16,100	158	8.76	1.35	73.4
44	54,800	208	2.42	1.45	147
45	45,400	148	2.74	1.54	99.8
46	109,000	371	2.36	1.32	269
47	181,000	530	2.34	1.24	387
48	228,000	550	2.10	1.23	417
49	143,000	583	3.19	1.22	385
50	127,000	525	3.20	1.24	346
51	108,000	471	3.23	1.27	308
52	82,400	377	3.26	1.31	245
53	30,900	191	3.69	1.45	118
54	65,900	512	6.36	1.21	269
55	43,000	351	6.64	1.29	180
56	35,300	251	6.76	1.36	127
57	25,100	175	7.71	1.46	83.9
58	11,300	77.2	7.96	1.62	36.2
59	218,000	596	2.09	1.23	453
60	195,000	559	2.09	1.25	424
61	167,000	511	2.10	1.26	386
62	125,000	413	2.13	1.32	309
63	41,900	178	2.17	1.51	130
64	220,000	546	1.88	1.24	430
65	195,000	508	1.88	1.25	399
66	152,000	425	1.90	1.29	331
67	224,000	499	1.73	1.24	404
68	197,000	473	1.74	1.26	382
69	150,000	387	1.75	1.29	310
70	224,000	456	1.69	1.26	371
71	174,000	405	1.69	1.29	328
72	187,000	500	2.44	1.24	361

CHAPTER V

DISCUSSION OF RESULTS

The experimental results obtained in this investigation for water-suspensions are compared with the heat transfer relationship for homogeneous liquids, equation 2, in Figure 6. Also included for comparison are data for suspensions of chalk, graphite, and copper obtained by Bonilla, et al., Miller, and Salamone, respectively. Only the suspensions of higher concentrations reported by these three investigators have been recalculated and presented here, in order that comparison with equation 2 might be conducted for the more stringent conditions. The recalculated data for the water runs of each investigator and for the kerosene runs of Miller are also shown in Figure 6.

Thus, Figure 6 consolidates data of four separate studies of liquid-solid suspensions flowing turbulently through horizontal heated pipes. At any value of Reynolds number in the range of 11,000 to 230,000, agreement of the grouping $(\frac{hD}{k})/(\frac{C_p\mu}{k})^{1/3}(\frac{\mu}{\mu_w})^{0.14}$ with the equation for homogeneous liquids is within a maximum deviation of approximately ±25 per cent, except for several water-graphite suspension runs of Miller and a few chalk suspension runs. Representation of the data by equation 2, in which the suspension physical properties have been evaluated according

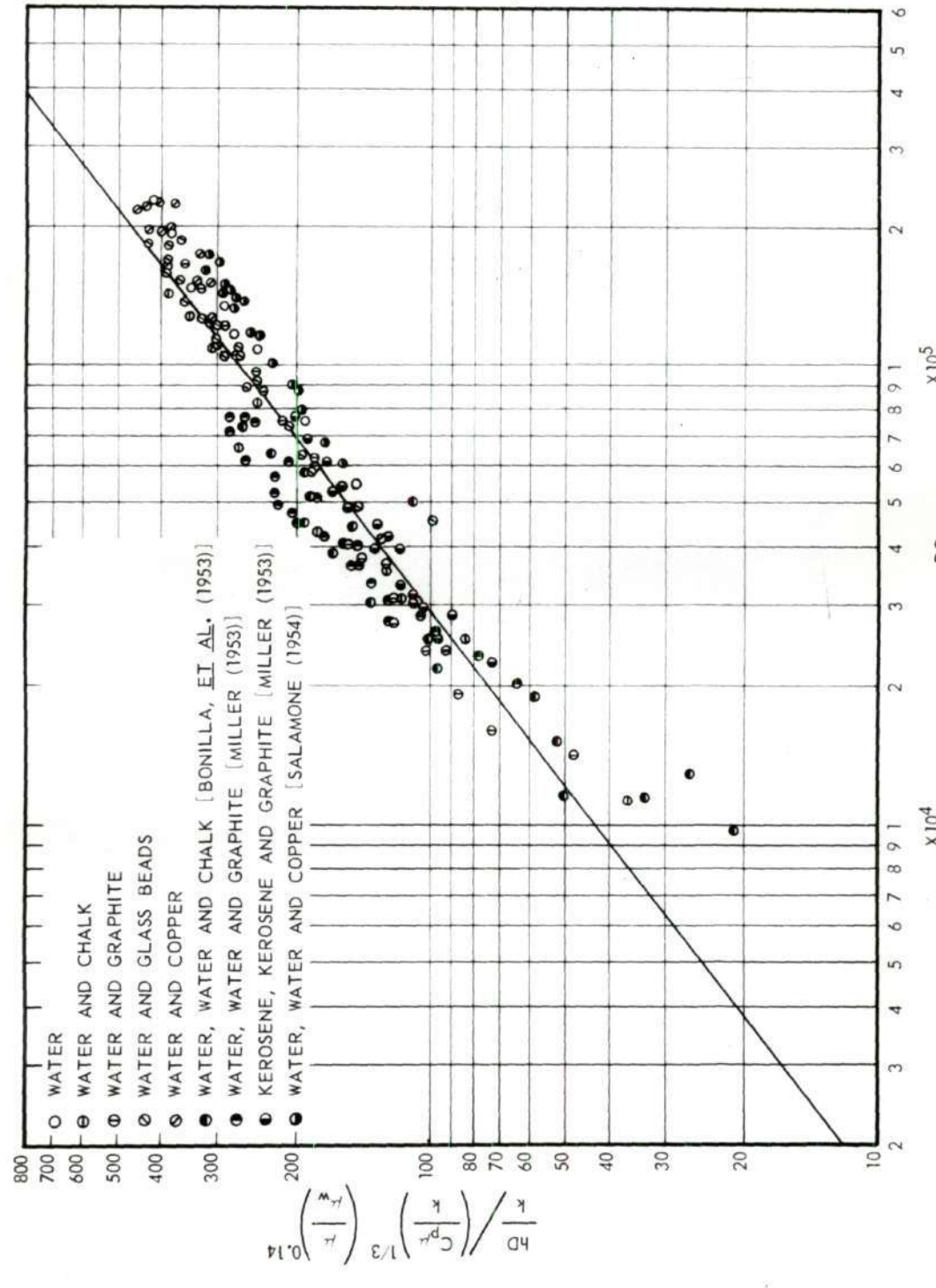

Figure 6. Calculated Heat Transfer Results for Liquid-Solid Suspensions Flowing Turbulently Through Horizontal Pipes. (The solid line represents equation 2.)

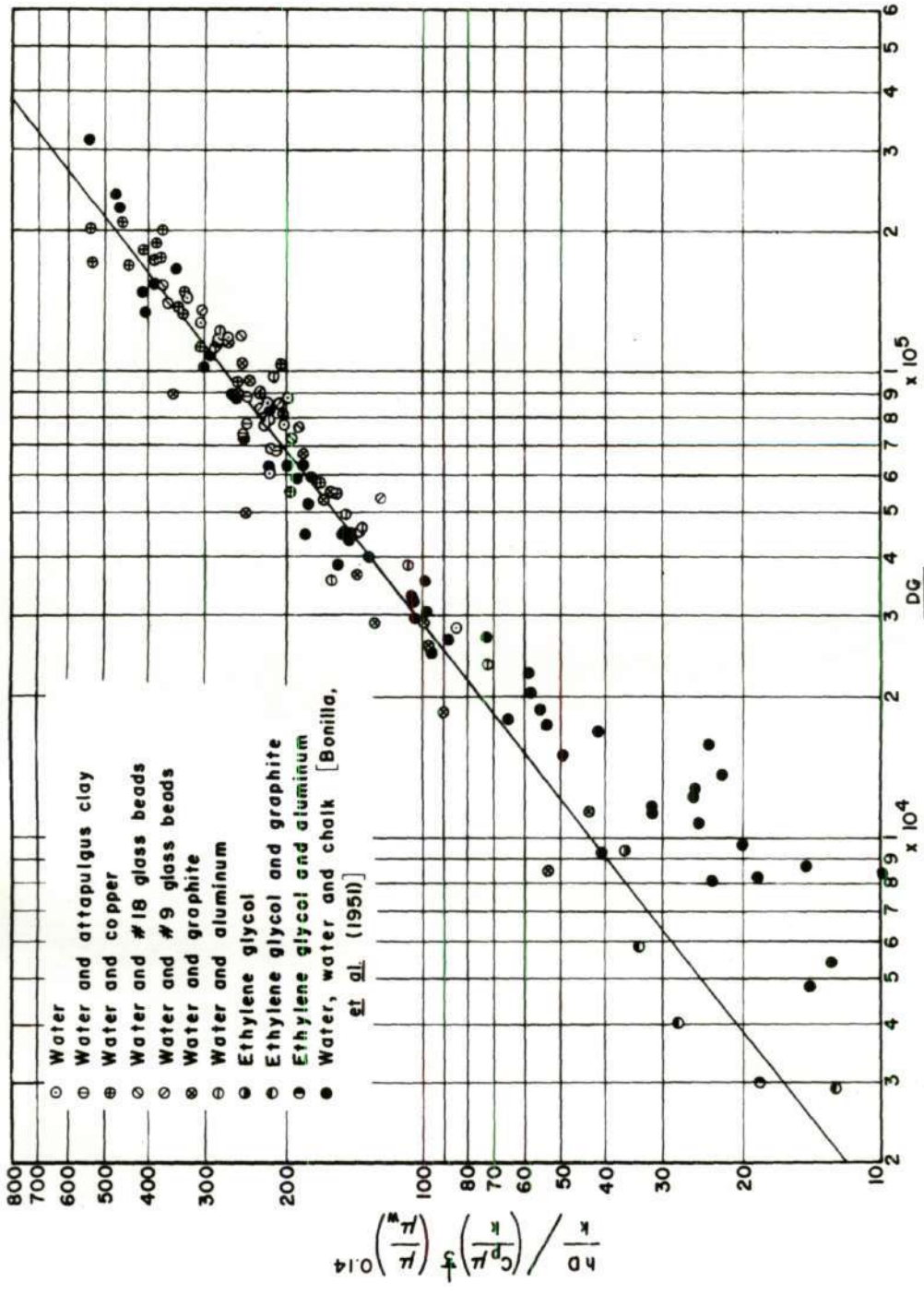

Figure 7. Calculated Heat Transfer Results for Liquid-Solid Suspensions Flowing Turbulently Through a Vertical Pipe. (The solid line represents equation 2.) [Data of Orr (1952); data of Bonilla, et al. (1951) also shown.]

to specific relationships, is satisfactory for most design purposes. The agreement is considered acceptable in view of the deviations reported between homogeneous liquid data and equation 2. Also, it should be noted that the heat transfer coefficients of Miller were not obtained according to the procedure used in this and in the other investigations. The difficulty encountered in the chalk suspension study will be discussed later.

The heat transfer data of Orr for suspensions in vertical turbulent flow are compared with equation 2 in Figure 7.

Suspension viscosity.--The deviations between the experimental heat transfer results and equation 2, as shown by Figure 6, are attributed primarily to the suspension viscosity evaluation. Errors in the determination of suspension heat capacity and suspension thermal conductivity are considered slight. The relationship used to calculate heat capacity has had extensive satisfactory employment, while that used to calculate thermal conductivity has had less frequent but highly satisfactory utilization.

As in previous investigations of heterogeneous systems, viscosity is the property which is the most difficult to measure or estimate. For design purposes, it is desirable to obtain a reasonably accurate value of suspension viscosity without having to perform an experiment, as in

the case in which a pipeline viscometer is used.* Ideally, suspension viscosity would be calculated by a relationship requiring only knowledge of liquid viscosity and suspension concentration. However, relationships requiring such meager information are usually adequate only for limited ranges of concentration and for specific substances. It is evident that some factor related to the nature of the solid particles must be introduced.

The suspension viscosity relationship proposed by Orr (1952) and used in this study requires, in addition to the basic information just mentioned, the determination of a factor characteristic of each solid material. This additional information (the volume fraction of solid material in a sedimented bed) is determined from simple measurements of weight and volume. Orr's convenient viscosity relationship, equation 6, has been found adequate for nine liquid-solid systems containing up to 45.7 per cent solid material by weight. Reproduced in Figure 12, Appendix III, is his experimental suspension viscosity data from which the empirical viscosity relationship was obtained.

It should be noted that there are two methods by which the ratio x_v/x_{vb}, required for the suspension viscosity

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*It should not be construed that the pipeline viscometer technique necessarily yields an accurate measure of suspension viscosity. Orr obtained equally unsatisfactory suspension heat transfer correlations by use of pipeline viscometer data and by use of the pure liquid viscosity.

relationship, might be determined. The method employed by Orr and used in the majority of the calculations of the present study was to evaluate each of the terms separately. The fraction by volume of solid material in the suspension, x_v, was calculated from the measured suspension density and from the density of the solid and of the liquid composing the suspension. The fraction by volume of solid material in a sedimented bed, x_{vb}, was determined by mixing a weighed quantity of the solid material with the liquid in a graduated cylinder and observing the volume of the sedimented bed after a long period of undisturbed settling. The value of x_{vb} listed in Table III for each solid material is the average value determined from several measurements on mixtures containing different amounts of solid material and liquid.

An equivalent method of determining the value of the ratio x_v/x_{vb} is to permit a sample of the suspension actually employed in the heat transfer study to settle undisturbed in a graduated cylinder. The ratio of sedimented bed volume to total suspension volume is then equal to x_v/x_{vb}. Usually several days of settling were sufficient to yield a constant value of sedimented bed volume.

The values of the ratio obtained by the two methods differed only slightly for suspensions of copper and of glass beads. However, better correlation of the heat transfer data for the graphite suspensions was obtained by use of the

experimentally determined value of x_{vb}. Conversely, better agreement for the chalk suspension data was achieved by use of the volumetric technique. The method used to determine the viscosities of suspensions of the other investigations presented here depended upon the individual situation, as will be discussed later.

In agreement with the contention of Reiner (1949), Orr's experimental viscosity data indicate that the change in suspension viscosity with temperature is entirely due to the change in the liquid's viscosity.* Therefore, equation 2 may be rewritten with suspension viscosity appearing in Reynolds and Prandtl numbers and with liquid viscosity, at the fluid and wall temperatures, appearing in the viscosity ratio term. As such, the equation can be solved for suspension viscosity in terms of pipe geometry, experimentally determined temperatures and mass flow rate, suspension heat capacity and thermal conductivity, and liquid viscosity. The resulting expression, together with data from the present investigation, is presented in Appendix III.

Suspension thermal conductivity.--The thermal conductivity relationship proposed by Tareef (1940), which was used in Orr's and in this investigation, has been discussed in the Introduction. Tareef also gave an analysis of equation 5

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*This is discussed in connection with equation 6 in the sample calculation presentation, Appendix II.

to show the effect of employing a solid material of high thermal conductivity.

Upon dividing numerator and denominator of the right side of equation 5 by k_L and substituting N for each resulting ratio of k_p/k_L, the equation may be written

$$\frac{k_s}{k_L} = \frac{2 + N + 2x_vN - 2x_v}{2 + N - x_vN + x_v} \quad . \tag{9}$$

For the case of solid particles of high thermal conductivity suspended in a medium of relatively low conductivity, all terms not containing N may be omitted from the above equation. The resulting approximation is, then,

$$\frac{k_s}{k_L} = \frac{N + 2x_vN}{N - x_vN} = \frac{1 + 2x_v}{1 - x_v} \quad . \tag{10}$$

Thus, a suspension containing 50 per cent by volume of a highly conductive solid material would have an approximate k_s/k_L value of only four. It is obvious, then, that the thermal conductivity of a fluid system cannot be greatly increased by the addition of a highly conductive solid material. Therefore, Bonilla, et al., (1951, 1953) and Miller (1953), who treated solid materials of relatively low and moderate thermal conductivity, respectively, were not seriously in error by using liquid conductivity rather than suspension conductivity. Even for employment of a highly

conductive solid material, the use of the liquid conductivity alone would seem preferable to the assumption that the conductivities are additive by volume.

Heat transfer rate.--The heat transfer rate which was used to calculate the average film coefficient of heat transfer was that rate determined from the rate of fluid flow, the fluid heat capacity, and the fluid temperature rise. A slightly higher rate of heat transfer was calculated for each run from the condensate flow rate and from the enthalpies of steam and condensate. This higher rate was partially due to heat loss through the uninsulated flanges at each end of the exchanger. In all but three of the runs, the heat transfer rates calculated for the steam were less than 10 per cent greater than the rates calculated for the fluid.

The rate of heat transfer from the condensing steam was used as a check on the reliability of the heat input to the fluid. The fluid heat rate was used in the calculations because the measured and calculated quantities relative to the heat transfer fluid were considered more accurate than those for the steam and condensate. Also, employment of heat transfer rates based on conditions of the fluid is the usual design procedure.

Discussion of individual systems.--Information relative to the calculation and correlation of data for suspensions of the four solid materials is presented below.

(1) Glass bead suspensions. Data for the water suspensions of glass beads gave excellent agreement with equation 2. The x_{vb} value determined by Orr for similar glass beads was used to calculate the suspension viscosities in the present study.

(2) Graphite suspensions. Since the graphite used in Orr's study was also utilized here, the volume fraction of graphite in a sedimented bed as determined by Orr was used in calculating graphite suspension viscosity. Miller's data have been recalculated by using, in the viscosity relation, the ultimate bed volumes reported for 500-milliliter samples of his suspensions.

In calculating Miller's data for kerosene systems, the temperature variation of kerosene viscosity was obtained from data given by McAdams (1942) for a kerosene having similar A.S.T.M. distillation characteristics. It was necessary to employ this information in order to calculate kerosene viscosity at the pipe wall temperature.

Pipe wall temperatures for the data of Miller were calculated from the reported values of the heat transfer coefficient, the fluid temperatures, the heat transfer rate, and the inside pipe surface area. The temperature, thus obtained, was considered acceptable if its value was less than the temperature of the steam in the surrounding jacket. Any error introduced by

the above estimation was considerably reduced when the resulting liquid viscosity at the pipe wall temperature was raised to the 0.14 power.

As stated previously, data for several of Miller's water-graphite suspensions deviated by more than + 25 per cent from the predictions of equation 2. His data for water followed the same general trend as the water-graphite suspension data, but kerosene and the kerosene-graphite suspension gave excellent agreement with equation 2. Upon consideration of the possible sources of error, in general, the correlation of Miller's data would seem acceptable.

(3) Chalk suspensions. Four concentrations of water-chalk suspensions were investigated, but only the two containing 4.99 per cent and 13.9 per cent by weight are shown in Figure 6. During the initial period of operation with chalk suspensions, only the 4.99 per cent concentration was studied. The heat transfer apparatus was then cleaned by the circulation of a suspension of water and glass beads, and more concentrated suspensions were studied during the next operating period. The 13.9 per cent concentration was then investigated; more chalk was added, and higher concentrations were tested during the same period of operation. However, chalk was deposited steadily on the pipe wall so that, toward the end of the chalk

investigation, only negligible heat transfer was obtained. This fouling of the heat transfer surface made the high concentration chalk data meaningless.

Professor Bonilla furnished Orr the information by which the sedimented bed concentration was calculated for the chalk used in the investigation of Bonilla, et al. As noted previously, the viscosities of the present study on chalk suspensions were determined by utilizing the ratio of bed volume to suspension volume for samples of the water-chalk suspensions studied.

(4) Copper suspensions. The average particle size of the copper used by Salamone was approximately the same as that used in Orr's investigation and in the present study. Therefore, the x_{vb} value determined by Orr for powdered copper was used in calculating the viscosity of water-copper suspensions. The results of the present investigation are in close agreement with the re-calculated data of Salamone. As shown in Figure 6, the water-copper suspension data are below the line representing equation 2. The deviation increases for increasing Reynolds numbers and for higher copper concentrations.

Discussion of the correlation.--Except for the discrepancies noted and discussed previously for certain water-graphite and water-chalk runs, the data plotted in Figure 6 appear to follow a general trend. The best line drawn through the

points would obviously have a slope slightly less than the slope of 0.8 required for equation 2. However, the purpose of this investigation was to make a comparison with equation 2, and since the agreement was satisfactory, other possible representations of the data were not determined.

The correlation of heat transfer data is affected by the manner in which pipe wall temperatures are obtained. In this investigation, as in Orr's, the pipe wall temperatures were found to vary linearly along the heat transfer pipe. As expected, the temperature of the upper pipe wall was slightly higher than the temperature of the lower wall -- generally from 1^{o} F. to 3^{o} F. higher. However, in several instances a reversal of the above effect was noted. This may be attributed to error in the temperature measurement and to possible change of thermocouple calibration with time.

End effects were taken into consideration by extrapolating the line through the temperature data; the terminal temperatures, thus obtained, represented the linear temperature distribution. The pipe temperature at the fluid outlet was generally higher than the inlet pipe temperature by about 10^{o} F.

The pipe wall temperatures reported for the data of Bonilla, et al., and of Salamone were the values obtained through averaging the temperatures indicated by three thermocouples in the upper pipe wall and by three in the lower wall. These investigators, therefore, employed a

single pipe wall temperature for each run. From pipe temperature data of Salamone (1954), several pipe wall temperature plots were attempted in accordance with the methods of the present investigation. Since Salamone had located two thermocouples at the center and two at each end of his heat transfer pipe, deviations, which were probably due to end effects, made it impractical to employ any temperature distribution other than a constant pipe wall temperature.

The six thermocouples used to measure pipe wall temperatures in the study of Bonilla, et al., were similarly spaced along the pipe. Miller employed the same thermocouple locations as Bonilla, et al. As noted previously, Miller made only two runs in which pipe wall temperatures were recorded, and the heat transfer coefficients for all other runs were determined by the Wilson (1915) method.

With regard to the range of variables covered by the correlation of Figure 6, reference to Table V will indicate the range of physical properties for the solid materials studied. The heat transfer fluids afforded the following variations in physical properties: thermal conductivity of 0.387 Btu/hr.,ft.^{2}(^{o}F.per ft.) for water to 0.661 Btu/hr.,ft.^{2}(^{o}F.per ft.) for the 32.5 weight per cent graphite suspension; heat capacity of 0.475 Btu/lb.,^{o}F. for the kerosene-graphite suspension to that of water; viscosity

of 0.760 lb./hr.,ft. for water to 7.70 lb./hr.,ft. for the graphite suspension of highest concentration; and density of 49.2 lb./ft.^{3} for kerosene to 83.0 lb./ft.^{3} for the copper suspension of highest concentration. Besides the nominal 3/8-inch I.P.S. pipe used in this study, pipes of the following sizes were used for the other investigations reported here: 1-1/2-inch I.P.S. for chalk suspensions, 1-inch I.P.S. for graphite suspensions, and 1/2-inch I.P.S. for copper suspensions.

Reynolds numbers from 11,000 to 230,000 were employed for suspensions containing up to 32.5 per cent solid material by weight. It should be noted that this concentration was obtained in the present study, while the maximum concentration reported by the other investigators of horizontal flow was the 18.0 weight per cent chalk suspension studied by Bonilla, et al. Considerable coverage of the variables affecting the transference of heat to liquid-solid suspensions in horizontal turbulent flow has therefore been realized.

CHAPTER VI

CONCLUSIONS

The conclusions resulting from the present investigation may be summarized as follows:

1. For a liquid-solid suspension flowing turbulently inside a horizontal pipe, the average film coefficient of heat transfer between the pipe wall and the suspension is given by the relationship

$$\frac{hD}{k_s} = 0.027\left(\frac{DG}{\mu_s}\right)^{0.8}\left(\frac{C_{ps}\mu_s}{k_s}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

for the suspension concentrations studied if suspension thermal conductivity and viscosity are evaluated by the relationships of Tareef (1940) and of Orr (1952), respectively, and if other terms are evaluated in the usual manner.

2. The difference observed between the correlation of Orr (1952) for suspensions in vertical turbulent flow and the present correlation for suspensions in horizontal turbulent flow is that, whereas, a Reynolds number exponent of 0.8 suffices for the vertical flow situation, a slightly lower value seems to be required for the best correlation of heat transfer data for suspensions in horizontal turbulent flow.

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APPENDIX I

PHYSICAL PROPERTIES OF SUSPENSION MATERIALS

Particle size distributions of glass beads and of copper powder are shown in Figure 8. Sources and data on physical properties of suspension materials are given in Table V.

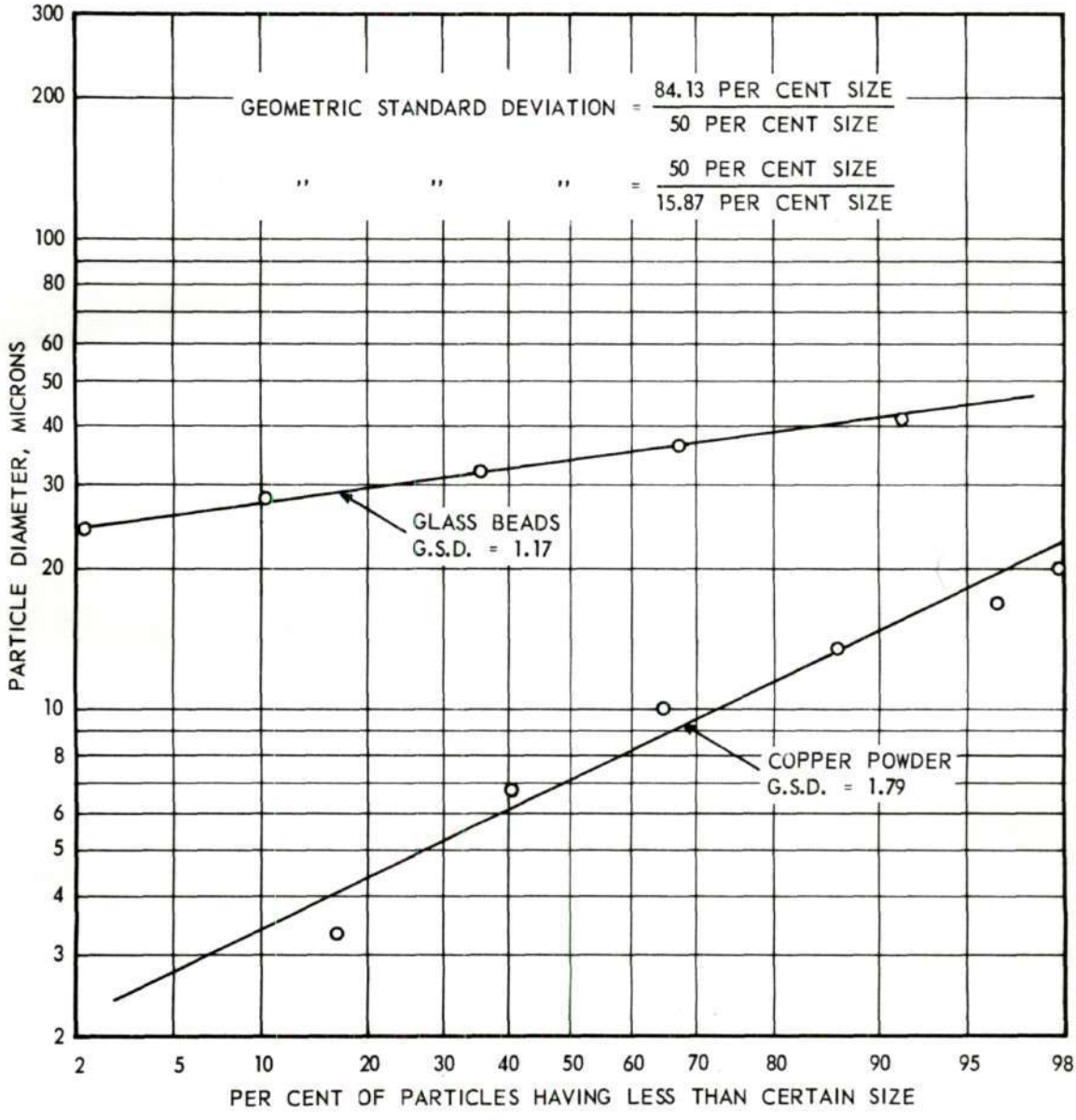

Figure 8. Size Distributions, on a Number Basis, of Copper Powder and of Glass Beads.

TABLE V. SOURCES AND PHYSICAL PROPERTIES OF SUSPENSION MATERIALS *

Material	Source	Density gm./ml.	Heat Capacity Btu/lb., °F.	Thermal Conductivity Btu/hr., ft.^{2} (°F./ft.)	Particle Size
Glass Beads	Minnesota Mining and Manufacturing Company	2.50 Smith (1955)	0.27 Smith (1955)	0.563 Smith (1955)	Median diameter of 33.5 microns, on a number basis, with a geometric standard deviation of 1.17.
Acheson Graphite	National Carbon Company	1.989 Orr (1952)	0.223 at 180°F. Perry (1950)	88.3 at 180°F. Powell (1937)	98.5% by weight passed a 200-mesh screen. Miller (1953) reported that 95% by weight passed a 48-mesh screen.
Precipitated Chalk	New England Lime Co. Adams, Mass.	2.71 Perry (1950)	0.214 Hodgman (1953)	0.4 McAdams (1954)	As reported by Barrett (1954), 99.7% passed a 325-mesh screen. Bonilla, et al. (1953) reported that 99.9% passed a 325-mesh screen.
Copper Powder	A. D. Mackay New York	8.92 Perry (1950)	0.0938 at 180°F. McAdams (1954)	218.7 at 180°F. McAdams (1954)	Median diameter of 7.0 microns, on a number basis, with a geometric standard deviation of 1.79. Salamone (1955) reported an average diameter of 21 microns, on a weight basis.

*The bulk mean fluid temperatures of this study were generally near 180°F. Miller reported an average temperature of 108°F. for his kerosene studies.

(Continued)

TABLE V. SOURCES AND PHYSICAL PROPERTIES OF SUSPENSION MATERIALS (Concluded)

Material	Source	Density gm./ml.	Heat Capacity Btu/lb., °F.	Thermal Conductivity Btu/hr., ft.^{2} (°F./ft.)	Viscosity lb./hr., ft.
Water	-	0.971 at 180°F. Hodgman (1953)	1.003 at 180°F. Perry (1950)	0.390 at 180°F. McAdams (1954)	0.840 at 180°F. McAdams (1954)
Kerosene	Standard Oil Company of California	0.788 at 108°F. Miller (1953)	0.490 at 108°F. Miller (1953)	0.0825 at 108°F. Miller (1953)	2.60 at 108°F. McAdams (1942), p. 181

APPENDIX II

SAMPLE CALCULATION

Run No. 31, employing a water-graphite suspension of 16.0 per cent graphite by weight will be used to illustrate the method of calculation. The experimental heat transfer data for this run are given on the sample data record in Figure 9. References and data for the physical properties of graphite and water are given in Appendix I. Necessary information relative to the copper heat transfer pipe are given below.

The nominal 3/8-inch standard I.P.S. copper pipe, through which heat was transferred, had a heated length of 8.21 feet. The pipe had an inside diameter of 0.0413 feet and an outside diameter of 0.0563 feet. The areas of the inside and outside heat transfer surfaces of the pipe were 1.064 square feet and 1.451 square feet, respectively. Therefore, the logarithmic mean heat transfer surface area was 1.247 square feet. The pipe had an internal cross-sectional area of 0.00134 square feet and a wall thickness of 0.0075 feet.

If it is assumed that no heat loss occurred through the insulated portions of the copper pipe, the suspension entered the exchange section at a temperature of 160.8°F. and left at a temperature of 202.8°F., as shown by Figure 10. Therefore, the physical properties of water and graphite were evaluated at the bulk mean suspension temperature, 181.8°F.

EXPERIMENTAL HEAT TRANSFER DATA

Water and GRAPHITE (Solid Material) Run No. 31
Date March 10, 1955

Barometric pressure, 29.0 in.Hg., 14.2 psi

STEAM

Main line pressure, 158, 155 psig; corrected avg. 150 psig, 164 psia

Approximate exchange-section pressure, 10.1 psig, 24.3 psia

Calorimeter temperature, 294.0 °F.

Condensate rotameter, 87, 87.5, 87; corrected avg. flow rate, 0.0445 ft^3/min.

Density of H_2O at 234.2 °F., 59.3 lb./ft^3; avg. flow rate, 2.64 lb./min.

SUSPENSION

Minimum pressure on fluid, 6.5, 6.5 psig; corrected avg. 7.2 psig, 21.4 psia

Manometer reading, 4.55/4.55 ; 4.55/4.55 in.Hg.; avg. press. drop, 9.1 in.Hg., 4.5 psi

Suspension rotameter reading, —

Suspension flow rate,

39 lb. 8 oz.; Tare, 5 lb. 12 oz.; Time, 30 sec.; Flow, 33.8 lb.

39	5	5	11	30	33.6

Average flow rate, 67.4 lb./min.

Suspension density,

2822 gm.; Tare, 968.8 gm.; Weight, 1853 gm.; Volume, 1707 ml.; Temp., 22 °C., 71.6 °F.

— — — — ρ = 1.086 gm./ml. —

Average density at 71.6 °F., 1.085 gm./ml., 67.7 lb./ft^3

Sedimented bed volume data,

Suspension volume, 241.5 ml.; bed volume, 112 ml.; Temp., 31 °C., 87.8 °F.

112/241.5 = 0.464 ; Avg. = 0.467

TEMPERATURES

* Thermocouple located on top of pipe; ( ) Position of thermocouple relative to the 0 - 98.5 inch heated length.

		mv.	°F.			mv.	°F.
Inlet	1. (-28.4)	3.018, 3.022	160.8	Exit	12. (109.3)	4.067, 4.071	202.8
	2* (4.2)	4.223	208.9	Tank	13.	2.993	159.9
	3. (4.6)	4.375	214.5	Cond.	14.	4.902	234.2
	4. (26.0)	4.521	220.0	2A*	(2.1)		
	5* (26.6)	4.531	220.4	3A.	(2.6)		
	6. (48.5)	4.573	222.0	7A*	(45.0)		
	7* (49.1)	4.611	223.4	8A.	(45.5)		
	8. (71.0)	4.639	224.5	10A*	(94.0)		
	9* (71.5)	4.652	225.0	11A.	(94.5)		
	10* (95.3)	4.699	226.7				
	11. (95.8)	4.697	226.7				

Tank thermometer, — °C., — °F.

Figure 9. Sample Experimental Data Record.

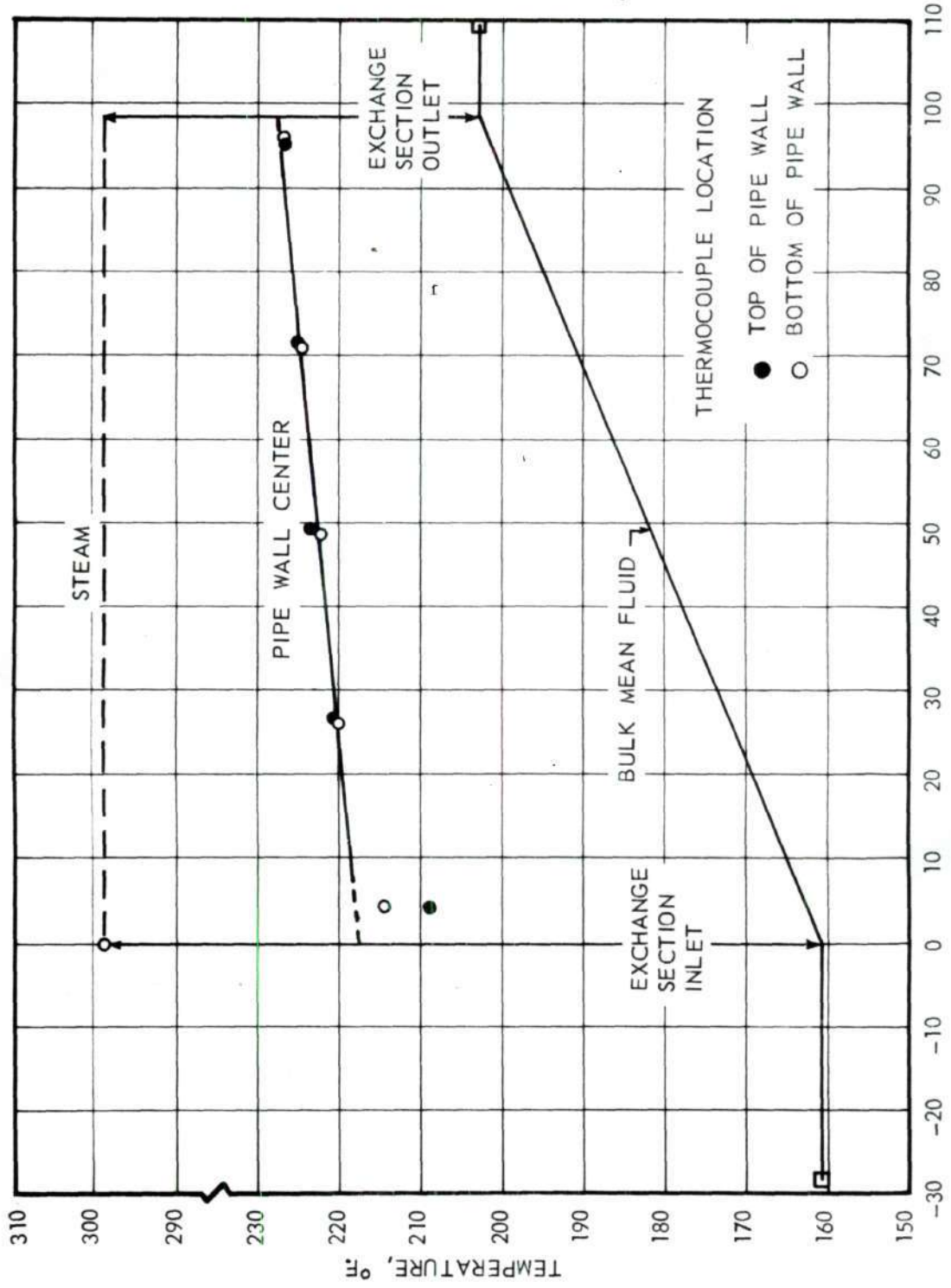

Figure 10. Temperatures Established in Heat Exchange Section for Run No. 31.

CALCULATED HEAT TRANSFER DATA

Water and GRAPHITE (Solid Material) Run No. 31
Date March 29, 1955

1. Suspension temperatures: Inlet 160.8 °F., Outlet 202.8 °F., Bulk mean 181.8 °F.
   $\Delta t = 42.0$ °F.
2. Water properties at bulk mean suspension temperature:
   Density 0.970 gm./ml., 60.5 lb./ft.^{3}; Viscosity 0.830 lb./hr.,ft.
   Thermal Conductivity 0.390 BTU/hr.,ft.,°F.; Heat Capacity 1.004 BTU/lb.,°F.
3. Solid material properties at bulk mean suspension temperature:
   Density 1.989 gm./ml., 124.2 lb./ft.^{3}
   Thermal conductivity 88.2 BTU/hr.,ft.,°F.; Heat Capacity 0.224 BTU/lb.,°F.
4. Suspension concentration:
   Avg. Weight % solids 16.0 ; Avg. Volume % solids 8.49 at bulk mean temp.
   Volume fraction solids expressed as fraction of sedimented bed vol.conc. 0.467
   $0.0849/0.264 = 0.322$
5. Suspension properties at bulk mean suspension temperature:
   Density 1.055 gm./ml., 65.8 lb./ft.^{3}; Viscosity 1.67 lb./hr.,ft.
   Thermal conductivity 0.498 BTU/hr.,ft.,°F.; Heat Capacity 0.879 BTU/lb.,°F.
6. Heat transferred: Enthalpy of steam 1190.1 BTU/lb.; condensate 202.5 BTU/lb.
   Heat to suspension 2490 BTU/min.; Heat from steam 2610 BTU/min.
   Error based on heat to suspension 4.8 %
7. Pipe wall temperatures -- Log mean temperature difference
   Pipe wall center temp.: Inlet 217.6 °F.; Outlet 227.6 °F.; Avg. 222.6 °F.
   Thermal conductivity of copper pipe at avg. wall temp. 217.8 BTU/hr.,ft.,°F.
   Temp. drop between pipe wall center and inside surface 2.2 °F.
   Inside pipe surface temp.: Inlet 215.4 °F.; Outlet 225.4 °F.; Avg. 220.4 °F.
   Viscosity of H_2O at avg. surface temp. 0.653 lb./hr.,ft.; Log mean Δt 36.3 °F.
8. Heat transfer coefficient 3870 BTU/hr.,Ft.^{2},°F.; Mass velocity 3,026,000 lb./hr.,ft.^{2}
   Re.No. (DG/μ) 74,800 ; Pr.No. $(C_p\mu/k)$ 2.95 , $(Pr.)^{0.33}$ 1.434
   Nu.No. (hD/k) 321 ; St.No. (h/C_pG) —
   μ_{H_2O}/μ_{H_2O}, wall temp. 1.27 ; $(\mu/\mu_w)^{0.14}$ 1.034 ; $Nu/Pr^{0.33}(\mu/\mu_w)^{0.14}$ 216

Figure 11. Sample Calculated Data Record.

The physical properties have been entered on the calculated heat transfer data record shown in Figure 11.

For the five runs of the 16.0 per cent concentration, the average suspension density was determined as 1.085 gm./ml. at the room temperature of 71.6°F. The density of graphite is 1.989 gm./ml., and the density of water at 71.6°F. is 0.998 gm./ml. The fraction by weight of graphite was then found from a simple material balance to be 0.160.

Suspension density at the bulk mean suspension temperature was calculated from the density measured at room temperature. The change in suspension density with temperature was assumed to be due entirely to the change in the water density. Since the density of water at the bulk mean temperature is 0.970 gm./ml., the suspension density at this temperature was, therefore,

$$1.085 \frac{\text{gm.}}{\text{ml.}} \times \frac{0.970}{0.998} = 1.055 \frac{\text{gm.}}{\text{ml.}} \text{ or } 65.8 \frac{\text{lb.}}{\text{ft.}^3} .$$

The fraction by volume of graphite in the suspension at the bulk mean temperature was then calculated as

$$0.160 \frac{\text{gm. graphite}}{\text{gm. suspension}} \times \frac{1.055}{1.989} = 0.0849 \frac{\text{ml. graphite}}{\text{ml. suspension}} .$$

Suspension physical properties were then calculated from relations which require the suspension concentration and the physical properties of water and of graphite.

The suspension heat capacity was calculated as the weighted average of the heat capacities of water and of graphite at the bulk mean temperature. Thus,

$$C_{ps} = (0.160 \times 0.224) + (0.840 \times 1.004) = 0.879 \ \frac{\text{Btu}}{\text{lb.,}^{\circ}\text{F.}} \ .$$

Upon substitution into equation 5, the thermal conductivity of the suspension was calculated to be

$$k_s = 0.390 \left[\frac{(2 \times 0.390) + 88.2 - (2 \times 0.0849)(0.390 - 88.2)}{(2 \times 0.390) + 88.2 + 0.0849(0.390 - 88.2)} \right]$$

$$= 0.498 \ \frac{\text{Btu}}{\text{hr.,ft}^2\text{(}^{\circ}\text{F.per ft.)}} \ .$$

Suspension viscosity was calculated by substitution into equation 6. Thus,

$$\mu_s = \frac{0.830}{\left(1 - \frac{0.0849}{0.264}\right)^{1.8}} = 1.67 \ \frac{\text{lb.}}{\text{hr.,ft.}} \ .$$

The rate of heat transfer to the fluid was calculated to be

$$67.4 \ \frac{\text{lb.}}{\text{min.}} \times 0.879 \ \frac{\text{Btu}}{\text{lb.,}^{\circ}\text{F.}} \times (202.8 - 160.8)^{\circ}\text{F.} = 2490 \ \frac{\text{Btu}}{\text{min.}} \ .$$

The enthalpy of superheated steam at the calorimeter pressure and temperature was determined from the data of Keenan and Keyes (1936) to be 1190.1 Btu/lb. This value was also considered to be the enthalpy of the steam entering the exchange section. The condensate was assumed to be saturated liquid at the condensate stream temperature, 234.2°F. The

enthalpy from Keenan and Keyes for the condensate leaving the exchange section was, therefore, 202.5 Btu/lb.

The rate at which heat was removed from the steam was then

$$2.64 \frac{\text{lb.}}{\text{min.}} \times (1190.1 - 202.5) \frac{\text{Btu}}{\text{lb.}} = 2610 \frac{\text{Btu}}{\text{min.}} .$$

This value was 120 Btu/min. or 4.8 per cent higher than the rate of heat transfer calculated from suspension data. For reasons stated in Chapter V, the value of 2490 Btu/min. was taken as the rate of heat transfer for all the calculations of this run.

The total mean temperature drop across the pipe wall was found to be

$$2490 \times 60 \frac{\text{Btu}}{\text{hr.}} \times 0.0075 \text{ ft.pipe wall thickness} \times \frac{1 \text{ hr.,ft.}^2\text{,}^\circ\text{F.}}{217.8 \text{ Btu,ft.}}$$

$$\times \frac{1}{1.247 \text{ ft.}^2 \text{ of heat transfer area}} = 4.1^\circ\text{F.}$$

For a pipe having the inside and outside diameters stated, it was shown by Orr (1952) that 54 per cent of the total temperature drop across the pipe wall occurs from the midplane of the pipe wall to the inner surface. Since the embedded thermocouples were assumed to indicate the temperatures at the midplane, the mean temperature drop across this portion of the pipe was then

$$4.1^\circ\text{F.} \times 0.54 = 2.2^\circ\text{F.} .$$

The logarithmic mean temperature difference was calculated from the terminal temperatures of the inside pipe surface and of the suspension. Thus,

$$\Delta T_m = \frac{\Delta T_i - \Delta T_o}{\ln \frac{\Delta T_i}{\Delta T_o}} = \frac{[(217.6 - 2.2) - 160.8] - [(227.6 - 2.2) - 202.8]}{2.303 \log \frac{[(217.6 - 2.2) - 160.8]}{[(227.6 - 2.2) - 202.8]}}$$

$$= 36.3^{\circ}F.$$

The average film coefficient of heat transfer, based on the logarithmic mean temperature difference, was calculated to be

$$h = 2490 \times 60 \frac{Btu}{hr.} \times \frac{1}{1.064\ ft^2} \times \frac{1}{36.3^{\circ}F.}$$

$$= 3870 \frac{Btu}{hr., ft^2, {}^{\circ}F.} .$$

The mass velocity was then calculated to be

$$67.4 \frac{lb.}{min.} \times \frac{60\ min.}{hr.} \times \frac{1}{0.001336\ ft^2} = 3,026,000 \frac{lb.}{hr., ft^2}$$

From the above quantities, the values of Reynolds, Prandtl, and Nusselt numbers were calculated.

$$\frac{DG}{\mu_s} = \frac{0.0413 \times 3,026,000}{1.67} = 74,800$$

$$\frac{C_{ps}\mu_s}{k_s} = \frac{0.879 \times 1.67}{0.498} = 2.95$$

$$\frac{hD}{k_s} = \frac{3870 \times 0.0413}{0.498} = 321 \quad .$$

Instead of employing water-graphite viscosities in the viscosity ratio, μ/μ_w, it is more convenient to use the value of water viscosity at each of the two temperatures. The two methods should yield the same ratio value since experimental data indicate that the temperature variation of suspension viscosity is entirely due to the change in the liquid's viscosity. However, upon consideration of the terms of equation 6, it is noted that x_v varies slightly with temperature while x_{vb} is a constant for each liquid-solid system. Therefore, equation 6 is in opposition to experimental evidence, but the small discrepancy is well within the limitations of the empirical suspension viscosity relationship. In all of the calculations of this investigation, liquid viscosities were employed in the viscosity ratio term.

For Run No. 31, the average inside pipe surface temperature was 220.4°F., at which temperature water has a viscosity of 0.653 $\frac{\text{lb.}}{\text{hr.,ft.}}$. Therefore,

$$\left(\frac{\mu}{\mu_w}\right) = \frac{0.830}{0.653} = 1.27 \quad .$$

For comparison of experimental data with equation 2, the grouping $Nu/(Pr)^{1/3}(\mu/\mu_w)^{0.14}$ was plotted versus Reynolds number on logarithmic coordinates. For this run,

$$\frac{Nu}{(Pr)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}} = \frac{321}{(2.95)^{1/3}\,(1.27)^{0.14}} = 216 \quad .$$

The method of calculation illustrated in the preceding paragraphs was applied to each of the seventy-two runs of this investigation and, as necessary, to the data of the other investigations presented here.

APPENDIX III

SUSPENSION VISCOSITY

The experimental suspension viscosity data of Orr (1952) are reproduced in Figure 12. The Sieder and Tate heat transfer relationship, as written for a suspension, was rearranged as an expression for suspension viscosity. Representative heat transfer data of this investigation were employed to yield the presentation of Figure 13.

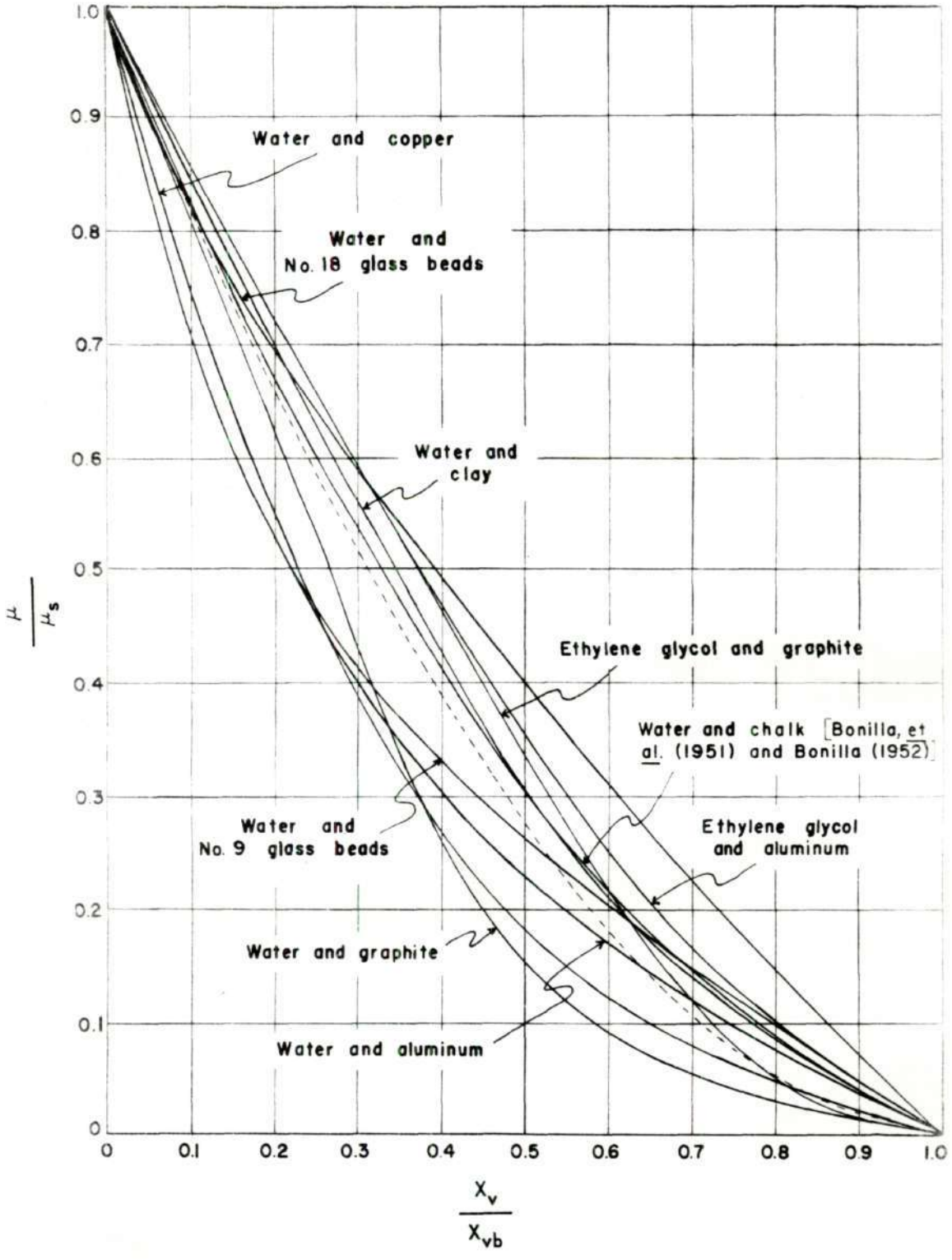

Figure 12. Experimental Suspension Viscosity Data from Which Equation 6 Was Obtained. [Data of Orr (1952).]

SUSPENSION "HEAT-EXCHANGER" VISCOSITY

The Sieder and Tate equation, as written for a suspension,

$$\frac{hD}{k_s} = 0.027\left(\frac{DG}{\mu_s}\right)^{0.8}\left(\frac{C_{ps}\mu_s}{k_s}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14},$$

may be rearranged to express μ/μ_s in terms of experimental heat transfer data and readily determined physical properties of the suspension and liquid. Thus,

$$\frac{\mu}{\mu_s} = \frac{\left(\frac{D}{4}\right)^{12/7}(W)^{3/7}(\mu_w)^{0.3}(\mu)^{0.7}}{(\pi)^{3/7}(.027L)^{15/7}\left(\frac{\Delta T_m}{\Delta T_s}\right)^{15/7}\left(\frac{k_s}{C_{ps}}\right)^{10/7}}.$$

The value of suspension viscosity, thus obtained from experimental quantities, is one that would require agreement of the experimental heat transfer results with the Sieder and Tate relationship.

In accordance with Orr's presentation of suspension viscosity data, the viscosity ratio is plotted versus the concentration ratio, x_v/x_{vb}, in Figure 13. The ratio x_v/x_{vb} has been determined by Orr's method in which x_v and x_{vb} are evaluated separately; the ratio was also determined by the graduated cylinder technique outlined in this report, whereby the ratio of ultimate bed volume to suspension volume

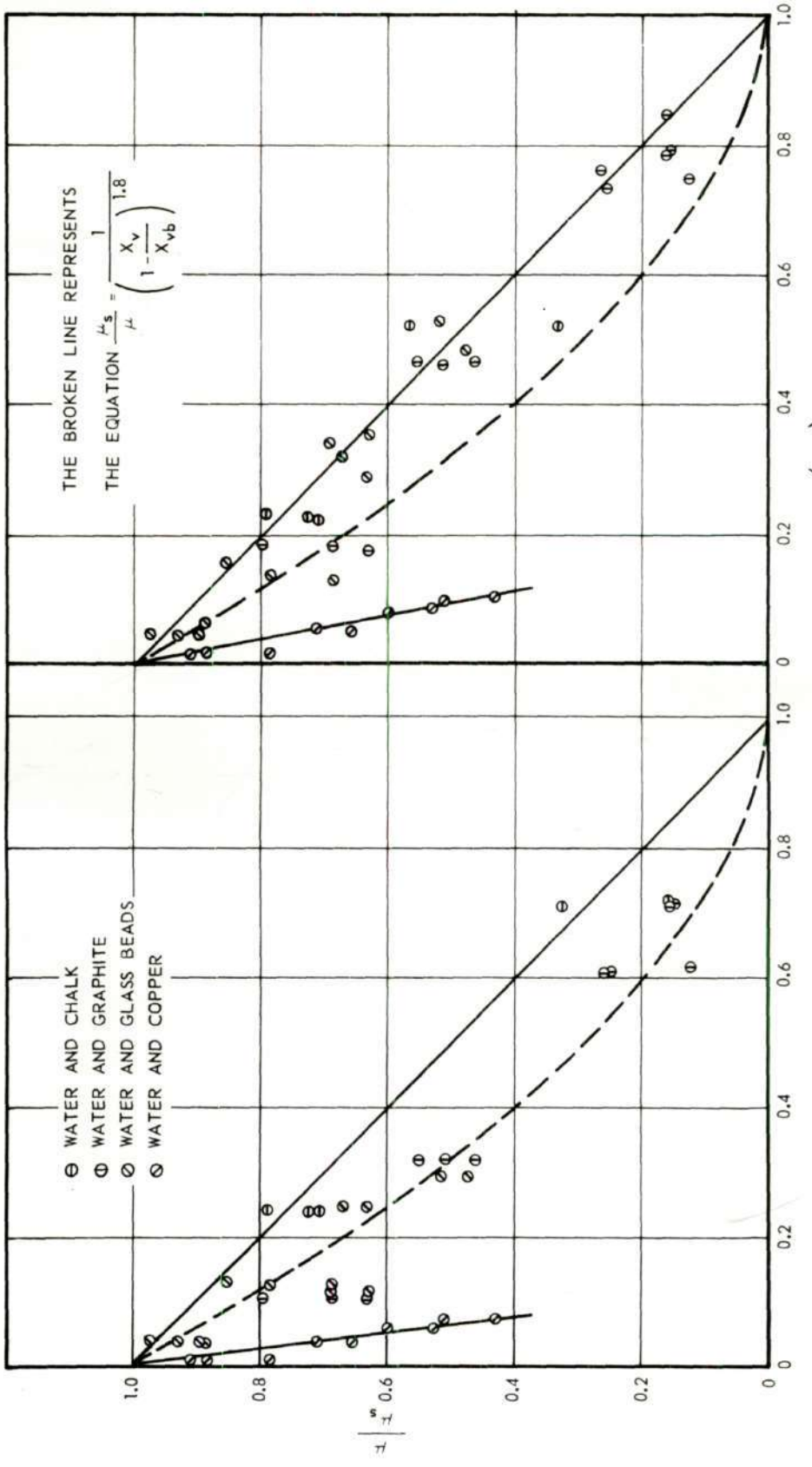

Figure 13. Suspension Viscosity Data Obtained by Substituting Heat Transfer Data into Equation 2.

is equivalent to x_v/x_{vb}. Representative runs for each of the suspensions studied in this investigation are presented in Figure 13.

While not in agreement with the data for water-suspensions of the three less dense materials, the data for the copper suspensions plot linearly in Figure 13 for both methods of the x_v/x_{vb} evaluation. For determination of the ratio by the graduated cylinder technique, the data for the less dense materials are definitely better represented by the equation

$$\frac{\mu_s}{\mu} = \frac{1}{(1 - \frac{x_v}{x_{vb}})}$$

than by the curve representing Orr's suspension viscosity relationship, equation 6. If the volume fraction x_{vb} is logically considered to be the concentration at which zero fluidity (i.e., infinite viscosity) occurs, then the agreement of the experimental data with the straight line is in accordance with the relationship of Bingham and Durham (1911),

$$\frac{\mu_s}{\mu} = \frac{1}{(1 - \frac{x_v}{x_{vo}})} \quad .$$

For the case in which the quantities x_v and x_{vb} were evaluated separately, the data for chalk, glass beads, and graphite are in better agreement with Orr's suspension viscosity relationship,

$$\frac{\mu_s}{\mu} = \frac{1}{\left(1 - \frac{x_v}{x_{vb}}\right)^{1.8}} \quad .$$

Through application of the above treatment to the various heat transfer relationships, further examination of experimental data might result in definite trends, if only for individual systems, which could prove useful as a suspension heat-transfer design tool.

APPENDIX IV

THERMOCOUPLE CALIBRATION

The calibration data for the fluid inlet, fluid outlet, and condensate thermocouples, together with data for two pipe-wall mounted thermocouples and two unmounted thermocouples, are given in Table VI.

TABLE VI

THERMOCOUPLE CALIBRATION DATA*

Temperature Indicated by Bureau of Standards Calibrated Thermometers (°F.)	Average Thermocouple Indication** (Absolute Millivolts)						
	No. 1	No.12	No.14	No. 3	No.10	No. 4	No. 9
100.9	1.561	1.564	1.564	1.535	1.571	1.536	1.574
124.6	2.138	2.140	2.140	2.108	2.153	2.109	2.155
151.9	2.803	2.804	2.804	2.765	2.816	2.767	2.816
174.8	3.364	3.365	3.365	3.329	3.375	3.330	3.375
201.5	4.032	4.035	4.034	3.998	4.046	3.998	4.046
226.0	4.684	4.687	4.686	4.654	4.697	4.654	4.698
248.7	5.283	5.285	5.284	5.244	5.294	5.247	5.298

*Thermocouples Nos. 1, 12, and 14 were mounted in copper tubes for insertion into the inlet mixing chamber, outlet mixing chamber, and condensate line, respectively. Thermocouples Nos. 4 and 9 were embedded in the wall of a short section of copper pipe.

**Average of three indications for each thermocouple at each temperature. Melting ice reference junction was used.

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VITA

Charles Marlin White, son of Lenora Simerville White and Charles Walter White, was born on January 17, 1928 in Rockmart, Polk County, Georgia. His wife is the former Miss Sarah Hancock of Decatur, Georgia.

Upon graduation from Rockmart High School in May 1946, he enlisted in the United States Marine Corps. The major part of his service was with a regimental intelligence section of the Second Marine Division, then at Camp Lejeune, N. C. After serving two years, he was discharged with the rank of sergeant.

In September 1948, he entered the Georgia Institute of Technology as a student in the School of Chemical Engineering. As an undergraduate, he was elected to membership in Phi Eta Sigma and Tau Beta Pi. In December 1951, he completed the requirements for the degree Bachelor of Chemical Engineering and was commissioned Second Lieutenant in the Army Chemical Corps Reserve.

He remained at the Georgia Institute of Technology to undertake graduate study in the School of Chemical Engineering, where he held a graduate assistantship until spring 1953. For the academic years 1953-54 and 1954-55, he was the recipient of the Socony-Vacuum Fellowship. He was elected to full membership in the Society of the Sigma Xi in June 1955.

During the summer of 1952, he was employed as an engineering assistant at the K-25 Gaseous Diffusion Plant,

Oak Ridge, Tennessee. In the summers of 1953 and 1954, he served as a graduate assistant with the Engineering Experiment Station, Georgia Institute of Technology. Upon completion of the requirements for the degree Doctor of Philosophy in Chemical Engineering, he was employed by the Esso Laboratories, Baton Rouge, Louisiana.